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THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

EDITED BY

GEORGE E. HALE
Mount Wilson Solar Observatory of the Carnegie Institution of Washington

EDWIN B. FROST
Yerkes Observatory of the University of Chicago

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Ryerson Physical Laboratory of the University of Chicago

JULY 1918

THE "ASTRONOMICAL ATOM" AND THE SPECTRAL SERIES OF HYDROGEN . . . *Fernando Sanford* 1

THE VARIATION WITH TEMPERATURE OF THE ELECTRIC FURNACE SPECTRA OF CALCIUM, STRONTIUM, BARIUM, AND MAGNESIUM . . . . . *Arthur S. King* 13

ON STELLAR EVOLUTION . . . . . *William Duncan MacMillan* 35

ON SOME PHENOMENA OBSERVED IN THE FOUCAULT TEST . . . . *Bernhard Dunn Bancroft* 50

MINOR CONTRIBUTIONS AND NOTES:
On Changes of the Wave-Lengths of Lines in Stellar Spectra with Change of Type, F. E. Baxandall, 59; *Suggestions to Observers of Nova Aquilae*, C. D. Perrine, 61.

NOTICE 63

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CONTENTS

NUMBER I

PAGE

THE "ASTRONOMICAL ATOM" AND THE SPECTRAL SERIES OF HYDROGEN. Fernando Sanford 1

THE VARIATION WITH TEMPERATURE OF THE ELECTRIC FURNACE SPECTRA OF CALCIUM, STRONTIUM, BARIUM, AND MAGNESIUM. Arthur S. King 13

ON STELLAR EVOLUTION. William Duncan MacMillan 35

ON SOME PHENOMENA OBSERVED IN THE FOUCAULT TEST. Sudhansukumar Banerji 50

MINOR CONTRIBUTIONS AND NOTES: On Changes of the Wave-Lengths of Lines in Stellar Spectra with Change of Type, F. E. Baxandall, 59; Suggestions to Observers of Nova Aquilae, C. D. Perrine, 61.

NOTICE 63

NUMBER II

THE VISIBILITY OF RADIATION. Edward P. Hyde, W. E. Forsythe, and F. E. Cady 65

STUDIES BASED ON THE COLORS AND MAGNITUDES IN STELLAR CLUSTERS. VI. Harlow Shapley 89

THE ABSORPTION OF NEAR INFRA-RED RADIATION BY WATER-VAPOR. W. W. Sleator 125

MINOR CONTRIBUTIONS AND NOTES: A Helium Star with Large Parallax, Radial Velocity (and Proper Motion?), J. Voûte, 144.

NUMBER III

ON THE EXCESS OF OUTWARD MOTION OF THE STARS OF CLASS B. C. D. Perrine 145

STUDIES BASED ON THE COLORS AND MAGNITUDES IN STELLAR CLUSTERS. VII. Harlow Shapley 154

350149

PAGE

ALPHA CENTAURI AS A SPECTROSCOPIC BINARY. Joseph Lunt . . 182

THE NATURE OF A SUPPOSED VARIATION IN THE SOLAR ROTATION IN 1915. Ralph E. DeLury 195

ERRATA 204

NUMBER IV

ON THE CONDITIONS IN THE INTERIOR OF A STAR. A. S. Eddington 205

THE VARIATION IN LIGHT AND COLOR OF RS BOÖTIS. Frederick H. Seares and Harlow Shapley 214

ARC AND SPARK SPECTRA AND THE PERIODIC SYSTEM. Ingo W. D. Hackh 241

MINOR CONTRIBUTIONS AND NOTES: Correction of Optical Surfaces, F. Twyman, 256; The Radial Velocity of 2 ω Leonis, Edwin B. Frost, 258; Preliminary Note on 66 Eridani, Edwin B. Frost, 260.

NUMBER V

THE RADIAL VELOCITIES OF 119 STARS OBSERVED AT THE CAPE. Joseph Lunt 261

STUDIES BASED ON THE COLORS AND MAGNITUDES IN STELLAR CLUSTERS. VIII. Harlow Shapley 279

ON THE CAUSE OF THE DISTANCE-VELOCITY EQUATION IN STELLAR MOTIONS. II. C. D. Perrine 295

THE CHANGE IN BRIGHTNESS, SPECTRUM, AND TEMPERATURE OF NOVA AQUILAE, No. 3. Mentore Maggini 303

THE PERIOD OF *004872* V TUCANAE. Bernhard H. Dawson . . 310

INDEX 319

THE
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VOLUME XLVIII JULY 1918 NUMBER 1

THE "ASTRONOMICAL ATOM" AND THE SPECTRAL SERIES OF HYDROGEN

By FERNANDO SANFORD

In a paper published in the *Astrophysical Journal* of November, 1916 (**44**, 201–209), the present writer was able to show that on the assumption that radiating electrons are revolving in elliptical or circular orbits about a central positive charge with velocities such that the photo-electric equation $\frac{1}{2}mv^2 = hv$ applies to them, their orbital radii may be computed, and that these radii bear a linear relation to the corresponding atomic radii computed from other considerations.

In a paper on "The Nuclear Charges of Atoms," published in the *Physical Review* of May, 1917 (**9**, 383), it was shown that on the same assumptions regarding the electrons which emit X-rays it is possible to compute the nuclear charges of the radiating atoms by means of Moseley's equations for X-ray frequency, and that these charges are, as suggested by van den Broek, simple multiples of the unit electrical charge.

It is the purpose of the present paper to discuss the spectral series of hydrogen on the same hypothesis.

As a justification for the fundamental assumption adopted in this and in the earlier papers, viz., that electrons while emitting

radiation are revolving in elliptical or circular orbits, it may be permitted to call attention to the fact that it is this assumption which has made it possible to calculate the correct value of e/m from the Zeeman effect. The hypothesis here used differs from that used by Zeeman only in assuming that the central force by which the revolving electrons are held in their orbits is electrical, while the Zeeman effect may be explained equally well by assuming this to be an elastic force of any kind.

As regards the use of the Einstein photo-electric equation, it seems to be experimentally proved that the energy of the cathode rays which give rise to the X-ray spectrum as well as the energy of the electrons which are liberated by the action of X-rays on metals may be calculated from the vibration-frequency of the induced or inducing X-rays by using the equation $\frac{1}{2}mv^2 = h\nu$, where ν is the vibration-frequency of the X-rays and h is the Planck radiation factor, viz., $6.55 \cdot 10^{-27}$ ergs/sec.

The same relation has been shown to hold in the case of electrons liberated by the action of ultra-violet light upon metals, and in the case of electrons which induce the single-line spectra in numerous elements. It accordingly seems extremely probable that it holds in the case of the other lines of a spectral series which lie between the ultra-violet rays and the less refrangible rays of the single-line spectrum.

The only new assumption involved in the use of the equation in this and the earlier papers referred to is that the kinetic energy of the free electrons is transformed into or results from the kinetic energy of orbital revolution.

It is well known that since the important discovery by Balmer that the wave-lengths of a group of lines in the hydrogen spectrum could all be expressed mathematically in terms of a single fundamental number, much attention has been devoted to the discovery and computation of spectral series. As a result of this work, a number of empirical formulae have been proposed by means of which the wave-lengths of certain groups of lines may be computed with considerable accuracy. These formulae, with the exception of some proposed by Ritz, have no theoretical basis, and all are merely empirical rules for calculating the wave-lengths under

consideration. Konen,[1] in referring to this fact, says that no relation between any of the constants used in these computations and any physical properties of the atom have ever been discovered. He admits as the one possible exception to this statement the relation between the ionic charges of certain elements and the convergence-frequencies of their corresponding spectral series, to which attention was called by the present writer in the *Astrophysical Journal* of October, 1912 (**36,** 255–262), but he ends by rejecting the ionic charges as true physical constants.

In this connection it seems to the present writer that the recognition by Rydberg of the fundamental frequency factor which he calls N is the most significant step in the theory of spectral series which has been made since Balmer's original discovery in 1885.

The discoveries which have resulted largely from the work of Barkla and the Braggs have shown that most elements emit one or more characteristic groups of X-rays which resemble in their spectra the visible band spectra of many substances. In many of the elements two of these X-ray spectral bands are known; in elements of the highest atomic weight only one band is known, and in a few of the lighter elements no characteristic X-rays have certainly been observed.

The general position of these spectral bands is given for each element by Moseley's equation, $\nu = A(N-b)^2$, where ν is the vibration-frequency which gives rise to the spectral line under consideration, N is the serial number proposed by Rydberg and van den Broek (not the Rydberg frequency factor N), and A and b are constants for a particular type of radiation.

With the exception of those physicists, if any there be, who advocate the Bohr hypothesis, there seems to be a consensus of opinion that visible radiation, including infra-red and ultra-violet, as well as X-radiation, is due in some manner to oscillations of electrons in an atomic system. This being the case, it would seem that whatever system of oscillating electrons gives rise to X-rays must form at least a part of the system which emits visible radiation.

There have been several hypotheses regarding the necessary structure of an atomic system which shall be capable of giving off

[1] *Das Leuchten der Gase und Daempfe*, p. 195.

discontinuous spectra similar to those which have been observed. The proposers of these hypotheses, with the exception of Ritz, have assumed that the radiating electrons oscillate under the influence of electric forces. At the present time opinion seems to favor some hypothesis similar to the one proposed by Rutherford, and for which Lodge has proposed the name "Astronomical Atom"; viz., of one or more electrons revolving about a central positive mass in which most of the inertia of the system is located.

It is plain that an electron revolving about a positive charge will set up an oscillating electric field which will be transmitted by the ether. The orbital revolution is necessarily only a temporary condition and can be maintained only while energy is being supplied to the system. The condition of the electron when not in revolution is not at present under consideration. The only question now raised is, Will such a rotation account for any of the known laws of radiation? Or, putting it another way, Will this assumption combined with either of the known laws of radiation, e.g., Einstein's law or Moseley's law, enable us to calculate the other known law from it?

The article on nuclear atomic charges already referred to has answered this question in the affirmative, since it showed that the nuclear charges calculated by means of Einstein's equation and the law of circular motion have the same value as those calculated from Moseley's law and the unit electrical charge.

If we consider the atom as a mere planetary system, we can see no reason why the electrons should revolve in certain fixed periods which are closely related in the atoms of different elements, or why there should be such a thing as a spectral series. A satellite may revolve about its primary at any distance if it has the proper tangential velocity. In the case of a single electron revolving about a positive central charge, it is only necessary that $mv^2/R = Qe/R^2$, where Q is the central positive charge and e the negative electronic charge. The case is different if we locate a number of electrons outside the primary charge. In this case each revolving electron reduces the effective central charge for all electrons whose orbits lie outside its own, so that we have three variables, Q, v, and R, to take into consideration. It will accordingly be necessary to use some equation besides the general equation for circular motion to

account for the possible spacing of a number of electrons around a positive charge.

Both of the equations which have been found to apply to X-rays are of the discontinuous character suggested by what has been said. One of them has a discontinuity based upon the serial number of the element and the other has one based upon the Planck radiation factor, h. This latter equation shows that not all frequencies of radiation are possible, but only those which radiate a definite quantity of energy at each revolution.

Let us combine this equation for energy radiated with the equation for circular motion and see what limitations are thereby imposed upon the latter.

Our fundamental equations are then as follows:

$$Qe/R^2 = mv^2/R, \text{ and } Qe/R = mv^2 \tag{1}$$

$$mv^2 = 2hv = 2hc/\lambda \tag{2}$$

$$v = 2\pi Rv. \tag{3}$$

We have here three equations involving the variables Q, R, v, and λ, and by means of these we may express any one of these variables in terms of one of the others and of known quantities or of a numerical quantity. In computing these relations the following values of constants are used:

$$h = 6.55 \cdot 10^{-27}.$$

$$e/m = 1.765 \cdot 10^{7} \text{ E.M.U.}$$

$$e = 4.774 \cdot 10^{-10} \text{ E.S.U.}$$

$$c = 2.9989 \cdot 10^{10}.$$

Then,

$$Q = hv/e\pi = 4.367\, v \cdot 10^{-18}. \tag{4}$$

$$v^2 = \frac{2hc}{m\lambda} = \frac{4.357 \cdot 10^{10}}{\lambda} \text{ and } v = \frac{6.60 \cdot 10^{5}}{\sqrt{\lambda}}. \tag{5}$$

$$\text{From (4) and (5), } Q = e\pi\sqrt{\frac{2h^3c}{m\lambda}} = \frac{2.882 \cdot 10^{-12}}{\sqrt{\lambda}}. \tag{6}$$

$$\text{From (1) and (4), } Rv = h/m\pi = 2.312. \tag{7}$$

$$\text{Also, } R = \frac{3.503 \cdot 10^{-6}}{\sqrt{\lambda}}. \tag{8}$$

Of course, many other similar relations may be shown.

The foregoing equations allow us to compute the kinetic energy of the revolving electrons from two distinct considerations. Thus, from equation (1), $\frac{1}{2}mv^2 = Qe/2R$; from the photo-electric equation, $\frac{1}{2}mv^2 = hv$. One of these equations involves the assumption of orbital motion and the other does not.

It is a frequent characteristic of the spectra of elements that there are several pairs of lines whose vibration-frequencies differ by a constant number. From the photo-electric equation the kinetic energies of the electrons which produce these lines must differ by a constant quantity, Δhv. Hence we may write $\Delta hv = \frac{e}{2}\left(\frac{Q_1}{R_1} - \frac{Q_2}{R_2}\right)$. I have computed these differences of energy by the two methods from seventeen pairs of lines in the thallium spectrum which differ by about 7791 vibrations per cm and both give the same value for the constant energy difference, viz., $1.54 \cdot 10^{-12}$ ergs/sec. The agreement is equally good for the two triplet series of mercury, the frequency-differences being alternately 4630 and 1766.

We may also test our equation for orbital motion in another manner. Thus the potential differences necessary to produce the single-line spectra of a number of elements have been determined, and the wave-lengths of the spectral lines are known. The velocity given to the inducing electrons by the potential difference required to set up the radiation may be calculated from the equation $v = 5.95\sqrt{E} \cdot 10^7$, where E is volts and v the electron velocity in cm/sec.

But v may be calculated in terms of the wave-length of the given spectral line from equation (5), viz., $v = 6.60 \cdot 10^5/\sqrt{\lambda}$. Equating these two values of v, we have $E = 1.23 \cdot 10^{-4}/\sqrt{\lambda}$.

In Table I are given the observed and calculated voltages necessary to produce the single-line spectra of a number of elements. It will be seen that in every case the observed value is just a little greater than the minimum theoretical value.

TABLE I

Element	λ	*E* Obs.	*E* Calc.
Mercury	2537	4.89	4.85
Zinc	3076	4.04	4.00
Cadmium	3260	3.81	3.77
Magnesium	2852	4.35	4.31
Calcium	4227	2.94	2.91
Strontium	4608	2.69	2.67
Barium	5536	2.24	2.22

Passing to the consideration of the spectral series of hydrogen, it is well known that the most successful equation for calculating the wave-lengths of a spectral series from a fundamental wave-length is the one proposed by Balmer for the series which has since borne his name. In addition to the Balmer series three other series have been successfully calculated in hydrogen. One of these was first discovered in stellar spectra by E. C. Pickering; another, generally known as the principal series, was made out by Rydberg; and still another was predicted by Ritz in the extreme ultra-violet and was discovered by Lyman.

If, as has been shown in the case of X-rays, the atomic charge is the variable quantity upon which the wave-length of the spectral lines is based, it should be possible to find a characteristic hydrogen charge which may serve as a starting-point for calculating the effective charge to which each spectral line is due.

We have seen that upon the hypothesis of a planetary orbit for each radiating electron its effective charge may be computed from the equation $Q = 2.882 \cdot 10^{-12}/\sqrt{\lambda}$. It is accordingly possible to compute this hypothetical charge for every line in the Balmer series, and if our hypothesis is correct these charges should be capable of computation in terms of a single charge by a serial formula of the same character as the serial formula for wave-length. Since in our equation for the central charge $Q \propto 1/\sqrt{\lambda}$, it will be

convenient to use the Balmer equation in the form $1/\lambda = 1/h\left(\frac{m^2-4}{m^2}\right)$. It should then be possible to calculate Q from this equation by writing $Q = A\sqrt{\frac{m^2-4}{m^2}}$. In this equation A becomes a fundamental atomic charge from which all the other charges are computed. To determine A we have only to calculate the charge corresponding to each spectral line from the equation $Q = 2.882 \cdot 10^{-12}/1/\lambda$ and to divide this charge by $\sqrt{\frac{m^2-4}{m^2}}$ for the corresponding line. The results of this computation for the first nine lines of the Balmer series and for the line for which $m = 31$ are given in Table II.

TABLE II

m	$\lambda \cdot 10^8$	$Q \cdot 10^{10}$	$A \cdot 10^{10}$
3	6563.07	3.558	4.776
4	4861.57	4.135	4.774
5	4340.53	4.373	4.774
6	4102.00	4.496	4.769
7	3970.33	4.574	4.774
8	3889.15	4.618	4.771
9	3835.51	4.656	4.775
10	3798.00	4.678	4.774
11	3770.73	4.694	4.773
31	3661.31	4.763	4.773

The foregoing values of the fundamental charge of hydrogen calculated from the Balmer series give a mean value of $4.773 \cdot 10^{-10}$ E.S.U., and we may write the equation for the effective charges corresponding to the lines of the Balmer series $Q = e\sqrt{\frac{m^2-4}{m^2}}$, where e is the unit electrical charge. This makes it possible to calculate the wave-lengths of all the lines in the Balmer series in terms of the unit electrical charge and the serial number of the line, thus, $\lambda = \frac{8.306 \cdot 10^{-24}}{e^2\left(\frac{m^2-4}{m^2}\right)}$.

This equation also enables us to give a physical meaning to the Rydberg frequency-constant N. Thus the Balmer formula is frequently written $1/\lambda = N\left(\frac{1}{4} - \frac{1}{m^2}\right)$. The corresponding equation for the central charge then takes the form $Q = A'\sqrt{\frac{1}{4} - \frac{1}{m^2}}$.

If we compute A' from this equation it necessarily comes out twice as great as A in the former equation, and our equation for Q becomes $Q = 2e\sqrt{\frac{1}{4} - \frac{1}{m^2}}$. Since the value of Q increases with an increase of m until it becomes $Q = 2e\sqrt{\frac{1}{4}}$, it necessarily gives the same value for the atomic charge as does the former equation.

It follows from this that the Rydberg frequency, N, is the frequency which would be given by an electron revolving about a positive charge $Q = 2e$.

For the Pickering series in hydrogen Ritz gives the formula $1/\lambda = N\left[\frac{1}{4} - \frac{1}{(m+0.5)^2}\right]$. This equation reduces to the same value for N as does the Balmer equation, and for $m = \infty$, $Q = 2e\sqrt{\frac{1}{4}}$.

Since this is a series which seemingly cannot be accounted for by the Bohr equation, and which Bohr accordingly regards as a helium series, it may be worth while to compute the value of the fundamental atomic charge from the wave-lengths of some of the lines of this group.

In Table III are given the values of $2e$ computed from the first eight lines of the Pickering series, using the equation $2e = \frac{Q}{\sqrt{\frac{1}{4} - \frac{1}{(m+0.5)^2}}}$, Q being calculated as before from the equation $Q = 2.882 \cdot 10^{-12}/\sqrt{\lambda}$.

The lines of the Pickering series accordingly give a mean value for $2e$ of 9.544, making $e = 4.772$.

The principal series of hydrogen lies in the ultra-violet, with the exception of a single line. Rydberg has calculated the position of this series from the formulae for the Balmer series and the Pickering series, and a number of the lines have been observed in hot stars, though not in the vacuum-tube discharge. The Ritz

formula for this series is $1/\lambda = N\left[\frac{1}{(1.5)^2} - \frac{1}{(m+1)^2}\right]$. It should transform into $Q = 2e\sqrt{\frac{1}{(1.5)^2} - \frac{1}{(m+1)^2}}$.

TABLE III

m	$\lambda \cdot 10^8$	$Q \cdot 10^{10}$	$2e \cdot 10^{10}$
3	5413.6	3.916	9.550
4	4542.4	4.276	9.545
5	4200.7	4.447	9.543
6	4026.0	4.542	9.542
7	3924.0	4.600	9.543
8	3860.8	4.641	9.549
9	3815.7	4.663	9.536
10	3783.4	4.686	9.544

The values of $2e$ computed from this equation and a few of the lines of the series are given in Table IV.

TABLE IV

m	$\lambda \cdot 10^8$	$Q \cdot 10^{10}$	$2e \cdot 10^{10}$
1	4687.88	4.207	9.540
2	2734.55	5.510	9.551
3	2386.50	5.900	9.547
4	2253.74	6.067	9.540
5	2187.60	6.158	9.540

The mean value of $2e$ is, from the foregoing table, 9.554.

It will be observed that while the principal series of hydrogen enables us to calculate $2e$ with the same degree of accuracy as the other series, it converges to a positive charge greater than e, viz., $Q = 2e\sqrt{\frac{1}{(1.5)^2}} = 6.366 \cdot 10^{-10}$. Since we know of no way of increasing the positive charge of a hydrogen atom except by abstracting an electron, it would seem that it must be possible to have a hydrogen atom with a nuclear charge of $2e$. Such an atom should give off radiation of higher frequency than one with a charge only half as great, and its spectrum should be looked for in the ultra-violet.

Ritz concluded from other considerations that there should be a series in hydrogen with the formula $1/\lambda = N\left(1 - \frac{1}{m^2}\right)$. This is a much simpler formula than the others, and it transforms into the equation $Q = 2e\sqrt{1 - \frac{1}{m^2}}$.

Three of the lines of this series were identified by Lyman, and their wave-lengths and the corresponding values of $2e$ are given in Table V.

TABLE V

m	$\lambda \cdot 10^8$	$Q \cdot 10^{20}$	$2e \cdot 10^{20}$
2	1216	8.258	9.302
3	1026	9.006	9.552
4	972	9.237	9.540

Since in this case the wave-lengths cannot be known with as great an accuracy as in the case of longer waves, the values of $2e$ do not agree as well as in the other series, but two of the three lines give values in close agreement with the values calculated from other series.

In this connection it may be interesting to recall that the α-particle, which is apparently the positive nucleus of the helium atom, is generally supposed to carry a positive charge $Q = 2e$. Accordingly, this series might belong to helium as well as to hydrogen, as far as our evidence goes. As a matter of fact, Lyman is unable to say positively to which element it does belong, since all of the foregoing lines appeared when the tube contained either gas. Lyman says,[1] "In connection with Bohr's speculations it is important to observe that λ 1216, which forms the first member of the Ritz series, occupies exactly the same position when obtained from helium as when it is produced in hydrogen."

The convergence wave-length of this series would be $\lambda = 912$. As Lyman found no lines shorter than about $\lambda = 900$ which could be attributed to hydrogen, though he found lines as short as $\lambda = 600$, it seems extremely probable that there are no lines in the hydrogen spectrum which require a greater nuclear charge than $2e$.

[1] *Astrophysical Journal*, **43**, 100, 1916.

The fact that the hydrogen atom may apparently exist in two electrical conditions, in one of which the central charge is e and in the other of which it is $2e$, raises the question as to which corresponds to the normal or so-called neutral condition of the atom. If the normal charge is e, the charge $2e$ must be caused by the abstraction of an electron from the normal atom, and the radiating system which gives rise to the principal series and the Ritz-Lyman series must be electro-positive. If, on the other hand, the normal atom has a central charge of $2e$, it would seem that the Balmer series and the Pickering series must be due to atoms which have captured an electron and have thus become electro-negative.

It is at least suggestive in this connection to recall that in his work on "Duration of Luminosity of Electric Discharge in Gases and Vapours"[1] Strutt found that the luminous hydrogen atoms which gave the Balmer series were universally electro-negative, and that when deflected to one side by an electric field they showed no traces of any other lines than those of the Balmer series.

There is so far no experimental evidence that either hydrogen or helium may give rise to X-rays. The Moseley equation for k-radiation would give for hydrogen $Q=2e(1-b)$ and for helium $Q=2e(2-b)$. If one accepts Moseley's value of $b=1$ for the k-radiation, λ_k for helium $=912$, and the Ritz-Lyman series in hydrogen and helium starts with the convergence wave-length of the X-ray spectrum of helium.

LELAND STANFORD JUNIOR UNIVERSITY
May 20, 1918

[1] *Proceedings of the Royal Society*, **94**, 88, 1917.

THE VARIATION WITH TEMPERATURE OF THE ELECTRIC FURNACE SPECTRA OF CALCIUM, STRONTIUM, BARIUM, AND MAGNESIUM[1]

By ARTHUR S. KING

APPARATUS AND METHODS

The methods used in this investigation for observing the temperatures at which spectral lines appear and the rate at which they increase with rising temperature have been the same, in the main, as those employed for the examination of other spectra.[2] The electric furnace was operated *in vacuo*, except for occasional tests under other conditions, and the spectra were photographed in the first and second orders of a 15-ft. concave grating mounted in the vertical spectrograph in the Pasadena laboratory.[3] Spectrograms made with a 1-meter concave grating were used for a few lines in the ultra-violet and extreme red to supplement those of higher dispersion.

To obtain the various spectra the furnace was charged with calcium metal in small pieces, strontium chloride or bromide, barium chloride, and magnesium metal, both as powder and as fragments cut from rods.

A temperature of 1650° C., produced by a potential of 15 volts applied to the graphite tubes regularly used, yielded a considerable number of lines for each element. This accordingly was taken as the low-temperature stage. As intervals of 350° showed distinctive changes in the spectra, temperatures of approximately 2000° and 2350° were chosen as the medium and high temperatures, respectively. The spectrum of each of the substances was photographed at still higher temperatures, but the change beyond 2350° consisted chiefly in a broadening of lines already present, with more frequent

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 150.

[2] *Mt. Wilson Contr.*, Nos. 66, 76, 94, 108; *Astrophysical Journal*, **37**, 239, 1913; **39**, 139, 1914; **41**, 86, 1915; **42**, 344, 1915.

[3] *Mt. Wilson Contr.*, No. 84; *Astrophysical Journal*, **40**, 205, 1914.

reversals. At these temperatures calcium, strontium, and barium gave strong continuous spectra, which tended, through the equalization of emission and absorption, to conceal most of the sharp lines, while those usually showing reversal appeared as wide absorption lines, often with a width of several angstroms. This rendered impossible any comparison with the relative intensities at lower temperatures, so that the useful plates were limited to a temperature range within which the spectra always consisted of emission lines.

For the identification of the lines and a comparison of their intensities with those of the vacuum furnace, the arc in air was used, with the result that certain lines, especially in the spectra of calcium and barium, showed notable differences in structure in the two sources. Lines which in the air-arc are extremely diffuse, often without a distinct maximum and sometimes showing only as wide hazy patches, appear in the vacuum furnace as sharp lines which permit of close measurement, two or three such lines sometimes taking the place of the diffuse arc line. The reduced pressure in the furnace is in a measure responsible for this condition, but other conditions in the arc discharge contribute to the effect. A somewhat detailed study has been made of lines of this type in the spectrum of barium, including their changes under various conditions of temperature and pressure and the measurement of their furnace wave-lengths. This has yielded a considerable addition to the list of barium lines in the ultra-violet. Their peculiarities will be discussed later in the paper.

The line-classification adopted in previous papers has been adhered to as closely as possible, but in the extension into the ultra-violet a limit is reached beyond which no lines are emitted by the furnace at the given temperature, even with prolonged exposure. This limit proceeds steadily toward shorter wave-lengths as the temperature rises and furnishes the chief point of resemblance between the emission of furnace lines and that of the continuous spectrum of an incandescent solid. The effect on the classification is that lines beyond the point where the lowest temperature gives a spectrum go automatically into classes not lower than Class III, while lines too far in the ultra-violet to be given by the medium temperature chosen must be placed in Class IV or V. It may

happen as a result of this method that lines such as λ 2852 of magnesium or λ 3072 of barium are placed in Class III because they are too short in wave-length to be produced at the low furnace temperature, though they are very strong when the temperature is sufficient to show a spectrum in this region. In the visible region lines of this character would probably go into Class I. Lines belonging to a series which extends into the ultra-violet cannot be expected to go as a whole into the same temperature class, since the ultra-violet members may not be produced by a temperature which, for members of the same series in the visible region, results in a high intensity. While this condition must be considered as entering into the method of classification, the character of a line is indicated clearly enough for most purposes by noting the intensities for those temperatures at which the line in question is radiated.

EXPLANATION OF THE TABLES

The first column of each table contains the wave-lengths of lines as measured by Exner and Haschek[1] in the spectrum of the arc in air. In the second column are wave-lengths on the international system. For calcium the measurements of Crew and McCauley[2] with the vacuum arc are used, as the structure of lines in this source is similar to that of furnace lines and their list is more complete than that of Exner and Haschek, frequently giving values for groups of two or three lines which blend into a hazy line in the arc in air. For strontium the measurements of Hampe[3] on the international system are entered in the second column, and for magnesium those of Nacken,[4] the source in each case being the arc in air. For barium the international wave-lengths, beginning with λ 3640, are those for the arc in air given by Schmitz;[5] but to the violet of this point measures of the barium lines in the vacuum furnace made by the writer, with the assistance of Miss Brayton of the Computing Division, have been used, since the vacuum furnace lines are more numerous and include components whose wave-lengths differ appreciably from those of the corresponding diffuse blends of the arc in air.

[1] *Spektren der Elemente bei normalem Druck*, Leipzig, 1911.

[2] *Astrophysical Journal*, **39**, 29, 1914.

[3] *Zeitschrift für wissenschaftliche Photographie*, **13**, 348, 1914.

[4] *Ibid.*, **12**, 54, 1913.

[5] *Ibid.*, **11**, 209, 1912.

The sign † adjacent to a wave-length refers to a remark at the end of the table, which often includes important data regarding the character of the line.

Following the plan of previous papers the remaining columns in the tables give the intensity estimates for lines in the arc and for three furnace temperatures. The method of assigning lines to classes is also the same. Nebulous lines are indicated by "n" after the value of the intensity, very pronounced haziness being denoted by "N." The letters "r" and "R" indicate partial and complete self-reversal. Lines of Class I and Class II are strong at low temperature, those of Class II strengthening more rapidly as the tube becomes hotter, while Class I includes the lines for which the low-temperature furnace is especially favorable. Lines of Class III are absent or faint at low temperature, but appear at medium temperature, and are usually considerably stronger at high temperature. Class IV appears at the highest furnace temperatures, while Class V is usually absent in the furnace or, if present, the lines are faint compared with their arc intensities. "A" after the class number indicates that the line in question is relatively weak in the arc—usually not more than half as strong as in the high-temperature furnace.

For calcium and strontium a column headed "Series" is introduced, in which a line is placed in a proper pair, triplet, or "single-line" series according to the notation of Saunders.[1]

CALCIUM

Table I indicates the relative condition of the calcium lines for various furnace temperatures and for the arc in air. The number of lines in the furnace spectrum is practically the same as that observed by Crew and McCauley in the vacuum arc, the low pressure bringing out certain lines which in the arc in air are either quenched or blended with neighboring widened lines. Many calcium lines retain a high intensity at low temperature. In the red, certain lines are especially strong at medium temperature. Lines of Class V are found in the strong arc pairs λλ 3159, 3179 and λλ 3706, 3737, which have not been obtained in the furnace. The flame line λ 4227 dominates the furnace spectrum at all the temperatures

[1] *Astrophysical Journal*, **32**, 153, 1910.

TABLE I

Temperature Classification of Calcium Lines

λ Exner and Haschek	λ Crew and McCauley (I. A.)	Arc	Furnace			Class	Series
			High Temperature	Medium Temperature	Low Temperature		
2995.06	2994.953	5	5	1	.....	III	T
2997.41	2997.309	5	5	1	.....	III	p
2999.74	2999.651	4	4	1	.....	III	T
3000.96	3000.865	5	5	1	.....	III	
3006.97	3006.864	6	6	2	.....	III	p
3009.30	3009.212	5	5	1	.....	III	T
.....	3107.388	1N	1	.....	.....	IV	T_2
.....	3117.656	1N	2	.....	.....	IV A	T_2
.....	3136.003	1N	4	1	.....	IV A	T_1
.....	3140.782	3N	6	1	.....	IV A	T_1
.....	3141.164		3	.....	.....	IV A	T_1
.....	3150.747	4N	8	2	.....	III A	T_1
.....	3151.280		3	.....	.....	IV A	T_1
3159.01	3158.877	10	.....	.....	.....	V	P_1
.....	3164.618	1N	1	.....	.....	IV	T_2
.....	3169.854	1N	2	.....	.....	IV A	T_2
3179.50	3179.340	15	.....	.....	.....	V	P_1
.....	3180.521	1N	4	1	.....	III A	T_2
3181.43	3181.283	4	.....	.....	.....	V	P_1
.....	3209.930	2n	6	4	.....	III A	T_1
3215.c	3215.145	5n	8	5	.....	III A	T_1
.....	3215.334		4	2	.....	III A	T_1
3225.6	3225.883	8n	10	6	.....	III A	T_1
.....	3226.129		5	3	.....	III A	T_1
3269.37	3269.090	1n	2	1	.....	III A	T_2
3274.95	3274.661	2	4	2	.....	III A	T_2
3286.35	3286.060	4	6	4	.....	III	T_2
3344.52	3344.508	8n	10	5	1	III	T_1
3350.25	3350.198	25n	15	8	2	III	T_1
.....	3350.361		10	5	1	III	T_1
3361.95	3361.918	35n	20	12	3	III	T_1
.....	3362.131		10	5	1	III	T_1
3468.70	3468.484	4	5	2	1	II	T_2
3475.01	3474.774	8	8	4	2	II	T_2
3487.82	3487.611	12	10	6	3	II	T_2
3624.19	3624.107	20	20	10	1	III	T_1
3630.87	3630.749	30	30r	15	3	III	T_1
3631.07	3630.973	15	15	5	1	III	T_1
3644.53	3644.400	40	40R	15	5	III	T_1
3644.90	3644.760	15	20	5	1	III	T_1
.....	3644.990	2	3	1	.....	III	T_1
.....	3673.448	1	4	1	.....	III A	t
.....	3675.307	2	8	2	.....	III A	t
.....	3678.240	3	12	3	.....	III A	t
3706.18	3706.022	10	.....	.....	.....	V	P_2
3737.06	3736.903	12	.....	.....	.....	V	P_2
.....	3748.374†	.....	6	.....	.....	IV A	t
.....	3750.349†	.....	12	1	.....	IV A	t
.....	3753.367†	.....	15	1	.....	III A	t

TABLE I—*Continued*

λ Exner and Haschek	λ Crew and McCauley (I. A.)	Arc	Furnace			Class	Series
			High Temperature	Medium Temperature	Low Temperature		
.....	3872.552†	?n	3	1	.....	III A	t
.....	3875.807†	?n	4	2	.....	III A	t
.....	3889.141†	.....	2	1	.....	III A	SL_3
3933.81....	3933.664	400R	60R	30	20	II	PH
3949.10....	3948.899	6	6	3	1	III	T_2
3957.22....	3957.054	10	10	6	2	III	T_2
3968.63....	3968.465	350R	50R	25	18	II	PH
.....	3972.578†	.....	3	1	.....	III	SL_3
3973.91....	3973.716	12	12	8	3	III	T_2
.....	4058.912	1n	1	.....	.....	IV	SL_2
4093.00....	4092.649	8	4	3	1	III	t
4095.30....	4094.944	12	8	6	2	III	t
4098.9	4098.552	15	10	8	3	III	t
.....	4108.554†	10N	8	3	.....	III	SL_3
4226.90....	4226.731	500R	1000R	500R	300R	I	SL
4240.61....	4240.455	6	6	2	tr	III	SL_2
4283.20....	4283.008	40	30R	30	30	I	p
4289.50....	4289.363	40	30R	30	30	I	T
4299.18....	4298.989	30	25R	25	25	I	T
4302.70....	4302.525	60r	50R	40	40	I	p
4307.90....	4307.738	45	35R	35	30	I	
4318.80....	4318.648	45	35R	35	30	I	T
4355.50....	4355.099	25	15	8	2	III	SL_3
4425.60....	4425.428	50	30R	40	30	I	T_1
4435.17....	4434.948	60r	50R	50	40	I	T_1
4435.88....	4435.673	40	25r	35	25	I	T_1
4455.00....	4454.765	80	70R	60	50	I	T_1
4456.10....	4455.875	40	25r	35	30	I	T_1
4456.84....	4456.612	10	10	10	5	II	T_1
.....	4507.854	1	1	.....	.....	IV	
4509.8	4509.446	3	3	1	.....	III	
4512.7	4512.281	5	5	2	.....	III	
4527.35....	4526.944	30	15	8	3	III	SL_2
4578.88....	4578.570	30	10	10	6	II	t
4581.77....	4581.414	40	15	15	8	II	t
4586.22....	4585.868	50	20	20	12	II	t
4685.35....	4685.264	12	6	3	.....	III	
4847.38....	4847.292	2	5	1	.....	III A	
4878.38....	4878.132	50	25	20	4	III	SL_3
.....	5019.981†	.....	2	1	.....	III A	vp
5041.83....	5041.613	40	15	5	2	III	SL_2
5189.00....	5188.846	50	25	5	2	III	
5260.58....	5260.375	2	2	1	.....	III	
5261.87....	5261.701	20	20	10	2	III	
5262.40....	5262.238	25	25	12	2	III	
5264.41....	5264.237	20	20	10	2	III	
5265.73....	5265.559	40	40	30	4	III	
5270.44....	5270.272	60	60	40	6	III	
5349.69....	5349.470	25	20	8	2	III	
5513.16....	5512.978	20n	5	2	.....	III	
5582.20....	5581.973	25	20	10	2	III	

TABLE I—*Continued*

λ Exner and Haschek	λ Crew and McCauley (I.A.)	Arc	Furnace			Class	Series
			High Temperature	Medium Temperature	Low Temperature		
5588.94....	5588.746	80	50	50	8	III	
5590.30....	5590.109	20	15	10	2	III	
5594.70....	5594.464	60	40	40	6	III	
5598.69....	5598.484	50	50	30	4	III	
5601.50....	5601.283	30	30	10	2	III	
5603.09....	5602.829	25	20	10	2	III	
5857.69....	5857.476	100	80	15	2	III	
5867.89....	5867.578	1	1	.....	.....	IV	
6102.92....	6102.716	80	80	100	40	II	T_2
6122.49....	6122.216	100	80	150	60	II	T_2
6161.57....	6161.309	10	2	1	.....	III	
6162.41....	6162.177	150	60	150	70	II	T_2
6164.05....	6163.749	10	5	2	.....	III	
6166.70....	6166.443	15	10	5	.....	III	
6169.30....	6169.034	25	15	8	1	III	
6169.82....	6169.576	40	25	15	2	III	
6439.35....	6439.086	150	100	125	50	II	
6450.01....	6449.811	50	40	20	8	II	p
6455.83....	6455.606	10	10	4	2	II	p
6462.80....	6462.576	125	80	100	40	II	
6471.90....	6471.659	40	30	15	6	II	
6494.02....	6493.789	80	60	60	25	II	p
6499.84....	6499.648	30	25	15	6	II	p
6573.00....	6572.783	8	30	150	100	I A	
6717.90....	6717.688	30	25	4	1	III	
.....	7148.123	10	12	12	5	II	p
.....	7202.161	3	4	4	2	II	p
.....	7326.099	2	2	1	.....	III	

Remarks

λ	
3748–3753.	Appear faintly in vacuum arc.
3872–3875.	In band at λ 3883.
3889.	Appears in vacuum arc.
3972.	Appears in vacuum arc.
4108.	Very hazy in arc; about 2 A wide.
5019.	Appears in vacuum arc.

used. Being very sensitive to widening influences, its intensity at a given temperature depends largely on the vapor density, as was noted in a previous investigation.[1] If a large quantity of vapor is present, as in the experiments which gave the intensities noted in Table I, the line changes from a narrowly reversed condition at low temperature to a great width at high temperature. A width of

[1] *Mt. Wilson Contr.*, No. 32; *Astrophysical Journal*, **28**, 389, 1908.

reversal of 6.6 A has thus been obtained, the wings of the line blending with the continuous spectrum. Its progressive strengthening with temperature increase would place it in Class II; but it is essentially a low-temperature line and is not notably strong at high temperature unless much vapor is present. It may properly be classified, therefore, as a special type belonging in Class I.

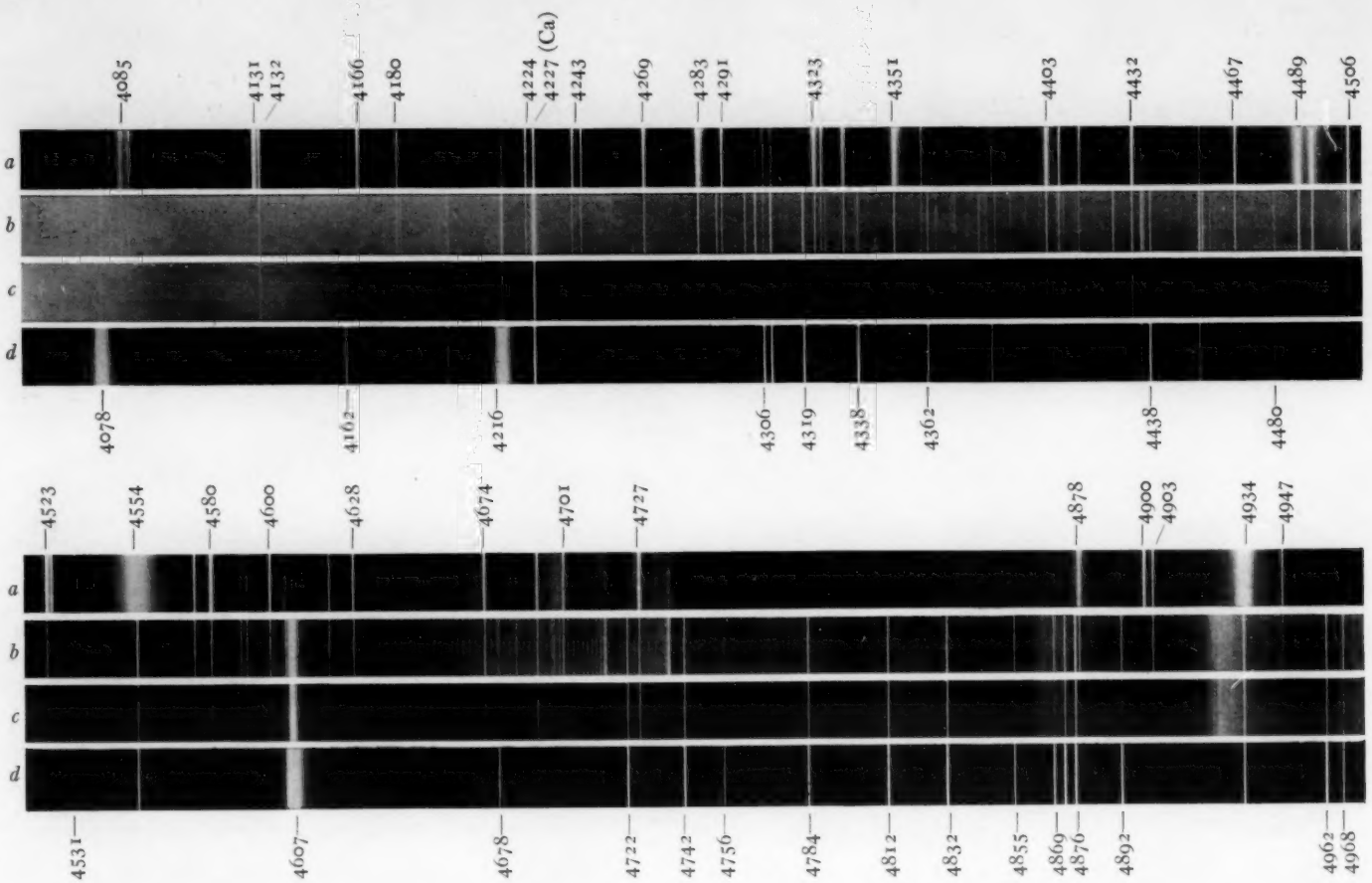
The H and K lines, λ 3934 and λ 3969, appear at temperatures as low as 1650°; they strengthen rapidly with temperature increase but remain narrow, though it is possible to obtain reversals at high temperature. Their intensities in the arc are enormously greater than in the furnace and offer in this respect a strong contrast to λ 4227.

A large proportion of the calcium lines having been placed in series, it is of interest to note their behavior at different temperatures. As would be expected, the component lines of a series pair or triplet are affected alike; but lines belonging to series groups in different parts of the spectrum may appear in different classes on account of the rapid falling off of the low-temperature spectrum as the wave-length decreases. Thus the intensities of T_1 series lines in the group which has its strongest line at λ 4455.00 are nearly equal at the three temperatures and the lines are assigned to Class I (with the exception of the component λ 4456.84), while the ultra-violet members of the same series fall off rapidly with decrease of temperature and are placed in Classes III and IV. To determine whether the ultra-violet members of a series weaken more rapidly when the temperature is reduced than those of greater wave-length requires careful attention to photographic differences, but this effect has occasionally appeared when furnace spectra at different temperatures were recorded on the same plate. Of the three groups with strongest lines at λλ 4455.00, 3644.53, and 3361.95 the more rapid falling off of the violet groups at reduced temperature was very distinct. This corresponds to the result previously observed for the principal series of caesium.[1]

The alternating single-line series SL_2 and SL_3 show a varied behavior but must be regularly classed as high-temperature lines. In the blue they show a decided contrast with the T_1 series lines

[1] *Astrophysical Journal*, **21**, 236, 1905.

PLATE I



FURNACE AND ARC SPECTRA OF BARIUM AND STRONTIUM

a. Arc spectrum of barium
b. Furnace spectrum of barium and strontium at 2050°
c. Furnace spectrum of barium and strontium at 1750°
d. Arc spectrum of strontium

and with the group of six near λ 4300. The several lines of this latter group, like those of the similar group near λ 3000, are affected alike at different temperatures.

In the region of greater wave-length the groups λ 5261–λ 5270 and λ 5582–λ 5603 behave in each case as a unit and their lines go into Class III. The lines farther to the red vary greatly in character, a notable feature being the high relative strength at the medium temperature in the case of several lines. λ 6573, whose high intensity in sun-spot spectra has been taken as evidence of the low temperature of these regions, is unique among the calcium lines, being faint in the arc and much weaker at high temperature than at the lower temperatures. Apparently it can be used with confidence as a low-temperature indicator.

STRONTIUM

The strontium lines are widely varied, but their notable features are for the most part sufficiently indicated by the data in Table II. The behavior of the strong lines λλ 4078, 4216, and 4607 in furnace and arc is very similar to that of their counterparts, H, K, and λ 4227 of the calcium spectrum. In the ultra-violet the arc gives a number of hazy, very unsymmetrical lines which reduce to sharp lines in the vacuum furnace, but without the complex structure sometimes observed for lines of this type in the case of barium. As in the case of calcium, the members of "single line" series are notably high-temperature lines. In the red there is a lack of the lines of Class I which appear in this region for both calcium and barium; excepting the strong lines λ 6408 and λ 6504 of Class II the dominant low-temperature lines are in the region of shorter wave-length.

Plate I shows the furnace spectra of a mixture of strontium and barium at temperatures of about 2050° and 1750° C., respectively, with the arc spectra of these substances above and below. The exposure times for the two temperatures were in the ratio of 11 to 1 and show lines of Class I, such as λ 4742 and λ 4812 of nearly the same intensity, while the larger gradations of lines in Classes II and III for these two temperatures are evident. The high intensity of λ 4607 in the furnace is shown, together with the relative faintness of λ 4078 and λ 4215.

TABLE II

Temperature Classification of Strontium Lines

λ Exner and Haschek	λ Hampe (I.A.)	Arc	Furnace			Class	Series
			High Temperature	Medium Temperature	Low Temperature		
2569.55	2569.502	20	10	.....	.....	IV	SL_1
2932.00	2931.856	30	15	10	.....	III	SL_1
3301.86	3301.739	50	15	10	.....	III	T
3307.6	3307.548	50n	15	10	.....	III	p T
3322.40	3322.237	30	15	8	.....	III	
3330.20	3330.011	30	8	8	.....	III	
3351.45	3351.258	150	50	20	.....	III	p
3366.51	3366.339	50	30	12	.....	III	T
3371.10	.....	2	.....	.....	.....	V	
3380.98	3380.721	50	.....	.....	.....	V	P_1
3390.09†	.....	4N	3	2	.....	III	T_1
3400.39†	.....	8N	4	3	.....	III	T_1
3411.7	.....	12N	6	4	.....	III	T_1
3456.8	3456.52	8n	2	1	.....	III	T_2
3457.7	3457.54	15n	10	6	.....	III	T_1
3464.68	3464.470	50	.....	.....	.....	V	P_1
3475.09	3474.901	10	.....	.....	.....	V	P_1
3477.3	3477.2	8n	8	5	.....	III	T_1
3499.4†	3499.61	20n	10	8	.....	III	T_1
3504.9	3504.27	2n	1	.....	.....	IV	T_2
3547.8†	3548.1	15n	10	6	1	III	T_1
3577.5†	.....	2n	?	?	.....	III?	T_2
3628.7	3628.37	3n	2	1	.....	III	T_2
3629.1	3629.12	10n	6	3	.....	III	T_1
3653.30	3653.26	12n	6	4	.....	III	T_1
3654.0	3653.91	3n	3	1	.....	III	T_1
3706.0	3705.90	15n	8	5	1	III	T_1
3940.90	3940.806	20	8	4	.....	III	T_1
3969.40	3969.270	30	8	5	1	III	T_1
3970.12	3970.049	20	7	3	.....	III	T_1
4030.55	4030.386	40	15	8	1	III	T_1
4032.50	4032.387	20	12	3	.....	III	T_1
4033.25†	4033.19	6	?	?	.....	III?	T_1
4061.3	4061.1	8n	4	2	.....	III	t
4071.22†	.....	10n	6	3	.....	III	t
4077.89	4077.714	400r	40r	25	12	II	PH
4087.88	4087.46	12n	.....	.....	.....	V	t
4161.99†	4161.812	30	?	?	.....	IV?	P_2
4215.70	4215.515	300r	30	15	6	II	PH
4305.68	4305.459	40	15	5	1	III	P_2
4308.5	4308.13	20n	10	8	2	III	t
4313.7	4313.23	3n	4	2	.....	III	SL_2
4319.4	4319.090	25n	15	10	2	III	t
4326.64	4326.444	8	10	6	2	II	T_2
4338.2	4337.704	30n	20	12	3	III	t
4361.88	4361.710	20	20	15	4	III	T_2
4407.0	4406.11	10n	10	5	1	III	SL_3
4412.80	4412.620	4	5	4	1	III	

TABLE II—*Continued*

λ Exner and Haschek	λ Hampe (I.A.)	Arc	Furnace			Class	Series
			High Temperature	Medium Temperature	Low Temperature		
4438.21	4438.044	25	20	15	6	II	T_2
4451.99	4451.803	2	3	2	.....	III	
4480.9	4480.540	10n	10	5	.....	III	SL_3
.....	4531.340						
4531.52	.....	10	12	8	3	II	
.....	4531.359						
4607.51	4607.340	600R	600R	400R	300R	I	SL?
4678.4	4678.304	20n	10	8	2	III	SL_3
4701.2†	4700.7	2	?	.....	.....	IV?	
4704.35†	4704.0	2	?	1	.....	III	
4707.5†	4707.1	2	?	1	.....	III	
4714.35†	4714.0	3	?	2	.....	III	
4722.48	4722.272	30	25	25	20	I	p
4729.8	4729.48	4n	4	2	.....	III	
4742.08	4741.917	30	30	25	20	I	T
4755.60	4755.467	12n	10	4	1	III	SL_2
4784.51	4784.323	30	30	25	18	I	T
4812.03	4811.867	40	40r	30	25	I	p
4832.27	4832.075	50	50r	40	30	I	T_1
4855.20	4855.078	20	20	12	3	III	t
4868.92	4868.739	20	20	15	3	III	t
4869.45	4869.194	4	5	2	.....	III	t
4872.70	4872.485	40	30	25	20	I	T_1
.....	4876.062	15	20	15	8	II	T_1
4876.38	4876.323	20	20	20	10	II	T
4892.20	4892.009	25	25	20	6	II	t
4892.90	4892.666	5	5	3	.....	III	t
4962.43	4962.244	40	40	30	20	I	T_1
4968.03	4967.928	20	20	15	6	II	T_1
4971.79	4971.649	2	5	3	2	II A	T_1
5156.38	5156.068	8	8	6	1	III	SL_3
5213.22†	5212.968	3	3	2?	.....	III	
5222.50	5222.200	20	10	8	3	II	
5225.35	5225.110	20	10	8	3	II	
5229.51	5229.266	20	10	7	3	II	
5238.82	5238.548	30	15	12	6	II	
5257.10	5256.897	50	20	20	10	II	
5330.11	5329.816	8	8	5	1	III	SL_2
5451.20	5450.818 5450.834	15	15	10	2	III	
5481.19	5480.840	40	30	20	15	II	
5486.40	5486.121	15	15	10	2	III	
5504.50	5504.166	30	20	15	8	II	
5522.01	5521.752	25	20	12	5	II	
5535.10	5534.796	15	15	8	2	III	
5540.29	5540.033	15	20	10	2	III	
5543.44	5543.327	15n	12	3	.....	III	
5970.6	5970.103	12n	10	3	.....	III	
6159.15	6158.967	1	1	.....	.....	IV	
6272.32†	6272.052	2	3	?	.....	IV?	

TABLE II—*Continued*

λ Exner and Haschek	λ Hampe (I.A.)	Arc	Furnace			Class	Series
			High Temperature	Medium Temperature	Low Temperature		
6346.05†	6345.760	10	?	?	?	IV?	
6364.23	6363.932	8	8	5	1	III	
6370.23	6369.959	15	12	8	2	III	
6381.00	6380.740	30	20	15	3	III	
6386.84	6386.507	40	20	15	4	III	p
6388.50	6388.245	25	15	10	3	III	
6408.76	6408.465	100	60	30	20	II	
6446.89†	6446.676	12	6	?	?	III	
6466.01†	6465.788	10	4	?	?	III?	
6504.21	65c3.990	80	50	30	20	II	
6547.00†	6546.785	20	15	5	?	III?	
6550.59†	6550.253	60	25	8	?	III?	p
6617.50†	6617.268	50	20	10	?	III?	
6643.70†	6643.545	20	15	5	?	III?	

Remarks

λ	
3390–3400.	Wide and hazy in arc. λ from Kayser and Runge.
3411.	Wide and hazy in arc.
3499.	Shaded to violet in arc.
3547.	Shaded to violet in arc.
3577.	Disturbed by band.
4033.	Disturbed by band. λ from Kayser and Runge.
4071.	Measured by writer.
4161.	Very faint if present in furnace.
4701–4714.	Disturbed by carbon band.
5213.	Disturbed by band.
6272.	Disturbed by band.
6346.	Concealed by band.
6446–6466.	Disturbed by band.
6547–6643.	Concealed by band at low temperature.

BARIUM

Table III gives the characteristics of the furnace spectrum of barium. Since the grouping of lines according to series is not so marked as with either calcium or strontium, the chief feature to be noted in this respect is that the behavior of the strong lines λ 4554 and λ 4934 is similar to that of H and K of calcium and λ 4078 and λ 4216 of strontium, while the low-temperature line λ 5536 corresponds to λ 4227 of calcium and λ 4607 of strontium. The furnace results thus bear out the resemblance observed between these lines in other light-sources.

The differences of structure shown by furnace spectra for many lines in the ultra-violet as compared with the arc in air warranted

TABLE III

Temperature Classification of Barium Lines

λ Exner and Haschek	λ King (I.A.)	Arc	Furnace			Class
			High Temperature	Medium Temperature	Low Temperature	
2596.87		8n	5			IV
2647.42		2	2			IV
2702.70		8	3			IV
2739.38		3	1			IV
2785.36		15	8			IV
3071.72	3071.592	100R	100R	50R		III
3108.3	3108.21	10n	5	1		III
	3117.34	*	3n	1		III
	3117.638	*	3n	1		III
	3119.202	3N	2	1		III
	3132.602	*	8	5		III
	3135.72	*	8n	5n		III
	3137.700	*	10	5		III
	3155.336	*	10	5		III
	3155.673	*	10	2		III
	3158.046	*	12	4		III
	3158.54†	*	12N	6		III
	3165.598†	*	25	15		III
	3173.69	*	15n	10		III
	3183.156	*	30	15		III
3184.5	3183.96†	?N	15	8		III
	3193.912 †	*	25n	10		III
	3193.967 †			5		III
3204.5	3203.700†	25N	25	15		III
	3221.630 †	40N	30	20		III
	3222.188 †		40	25		III
3223.0	3222.441 †		8	3		III
3253.2	3253.067	5n	5	2		III
	3261.961 †	80N	50r	25		III
3263.0	3262.336 †		60R	25		III
3270.30	3270.115	4n	4	2		III
	3272.405	2n	2	1		III
	3281.503	70N	40r	20		III
3282.1	3281.772 †		15	6		III
3315.92	3315.753	8n	8	5		III
	3322.797 †	80N	50r	25		III
3323.3	3323.058 †		10	4		III
3357.15	3356.804†	80N	40r	25		III
3377.33	3376.975	80N	60R	35		III
	3377.391 †		20	10		III
	3413.835	3n	3	1		III
3420.70	3420.322		70R	40		III
	3421.008 †	100N	25	15		III
	3421.476 †		30n	15		III
	3426.453†	4n	3	?		III?
	3427.85	3n	3	1		III
3464.7 †	3463.741	?N	40	25		III
3501.31	3501.115	200R	150R	75r	20	II

* Not visible in barium arc in air, probably an account of extreme diffuseness.

TABLE III—*Continued*

λ Exner and Haschek	λ King Schmitz (I.A.)	Arc	Furnace			Class
			High Temperature	Medium Temperature	Low Temperature	
3525.30†	3524.975	8on	50r	25	2	III
3529.64	3529.480	15	10	6	.....	III
3531.8†	3531.345	30N	40	20	1	III
3545.00†	3544.663	8on	60R	30	3	III
3547.99	3547.696	20n	15	10	1	III
3562.19	3561.942	10	10	7	.....	III
3566.83	3566.660	10	8	6	.....	III
3576.24	3576.036	10	10	6	1	III
3577.81	3577.615	30	10	8	1	III
3579.91†	3579.670	8on	50R	30	5	III
3586.69	3586.505	10	10	6	1	III
3588.32	3588.099	10	10	7	1	III
3590.15	3589.950	3	8	4	.....	IIIA
3593.50	3593.204	15n	15	8	1	III
3599.62	3599.396	15	10	8	1	III
3611.20	3610.957	15n	15	10	1	III
3630.85	3630.641	40	30	20	3	III
3637.2 †	3636.832	40N	40r	20	2	III
.....	3639.715 Schmitz	2	2	1	.....	III
3640.56	3640.391	10	8	5	.....	III
3662.71	3662.523	15	8	6	.....	III
3664.82	3664.598	3	3	1	.....	III
3675.45	3675.268	2	1	1	.....	III
3688.8	3688.473	20N	15	8	.....	III
3701.90	3701.716	3	3	2	.....	III
3794.88	3794.771	15	15	10	2	III
3862.07†	3861.905	15	8?	8?	2	III
3889.43	3889.314	20	10	8	6	II
3891.90	3891.788	50	.....	.....	.....	V
3892.90	3892.653	20	10	7	2	III
3900.56	.....	2	2	2	.....	III
3906.15	.....	2	2	2	.....	III
3910.03	3909.922	40	20	15	8	II
3917.38	.....	4	4	3	.....	III
3935.91	3935.715	50	15	10	6	II
3938.03	3937.876	20	10	8	2	III
3945.3 †	3945.60	10N	15	7	.....	III
3947.5 †	3947.51	5N	8	4	.....	III
3975.6	3975.362	4n	5	2	.....	III
3983.06	.....	2	1	1	.....	III
3993.55	3993.395	80	20	12	6	II
3995.85	3995.663	30	15	10	2	III
3998.05	.....	3	2	2	.....	III
4026.55†	.....	2n	1?	.....	.....	IV?
4081.1	4081.347	6n	8	4	.....	III
4085.0	4085.322	30N	30	12	2	III
4087.6	4087.371	8n	20	8	.....	IIIA
4110.35	4109.884	2	1	1	.....	III
4130.83	4130.683	80	.....	.....	.....	V
4132.58	4132.444	20	20	20	15	I

TABLE III—*Continued*

Å Exner and Haschek	Å Schmitz (I.A.)	Arc	Furnace			Class
			High Temperature	Medium Temperature	Low Temperature	
4166.17.....	4166.017	20	.....	.....	.....	V
4179.58.....	4179.372	8n	20	10	.....	III A
4224.20.....	4223.957	12	20	12	2	III
4239.85.....	4239.576	10n	15	10	1	III
4242.80.....	4242.619	10	15	10	1	III
4264.45.....	4264.386	15n	30	15	2	III A
4283.31.....	4283.111	100	40	40	20	II
4291.33.....	4291.165	12	15	10	2	III
4323.05.....	4323.004	20n	35	20	3	III
4325.34.....	4325.152	10	15	10	1	III
4332.97†....	4332.919	10n	10?	10	2	III
4350.60.....	4350.375	80	35	30	12	II
4359.76.....	4359.554	5	8	5	.....	III
4402.80.....	4402.550	60	30	30	15	II
4407.07.....	4406.846	15	15	12	2	III
4413.89.....	4413.679	8	10	6	1	III
4432.10.....	4431.914	40	25	25	15	II
4467.30.....	4467.129	12	15	12	2	III
4489.10.....	4488.973	60n	50	35	6	III
4493.79.....	4493.641	50n	40	30	5	III
4506.13.....	4505.936	40	30	25	15	II
4523.48.....	4523.237	60n	40	25	12	II
4525.19.....	4524.946	35	.....	.....	.....	V
4554.21.....	4554.038	1000R	100r	80	70	II
4574.02.....	4573.881	40	30	25	15	II
4579.82.....	4579.667	80	40	30	20	II
4589.83.....	4589.762	8n	15	12	2	III A
4591.92.....	4591.825	10n	15	12	2	III
4599.97.....	4599.751	30	20	15	3	III
4605.10.....	4605.012	8n	15	8	2	III A
4620.19.....	4619.978	20n	15	8	2	III
4628.45.....	4628.330	25n	25	20	3	III
4636.7 †....	4636.333	15N	?	.....	.....	IV?
4642.5 †....	4642.038	4N	?	.....	.....	IV?
4652.0 †....	.....	5N	?	.....	.....	IV?
4663.0 †....	.....	10N	?	.....	.....	IV?
4673.75.....	4673.621	30	25	20	12	II
4691.85.....	4691.630	35	30	25	15	II
.....	4699.108†	15N	10	6	1	III
4700.67.....	4700.446	20	12	10	2	III
4724.96.....	4724.742	3	4	2	.....	III
4726.68.....	4726.455	40	30	25	15	II
4732.0 †....	.....	5N	?	?	.....	III?
4739.5	.....	5N	?	1	.....	III
4807.8	.....	2N	1	1	.....	III
4877.8	4877.650	30N	25	12	2	III
4900.11†....	4899.971	35	3?	.....	.....	IV?
4903.05.....	4902.898	15	15	10	2	III
4934.26.....	4934.099	700R	70R	60	50	II
4947.50.....	4947.350	8	10	4	1	III
5055.14†....	5054.975	5	?	?	.....	IV?

TABLE III—*Continued*

λ Exner and Haschek	λ Schmitz (I.A.)	Arc	Furnace			Class
			High Temperature	Medium Temperature	Low Temperature	
5160.10†	5159.919	20n	?	?	.....	IV?
5175.72†	5175.619	5	?	?	.....	IV?
5177.52†	5177.448	2	?	?	.....	IV?
5267.18†	5267.033	20	?	?	.....	IV?
5277.75†	5277.625	3	?	?	.....	IV?
5303.00†	5302.808	6	?	?	.....	IV?
5305.92†	5305.758	4	?	?	.....	IV?
5309.10†	5308.952	4	?	?	.....	IV?
5405.20	5404.920	5n	10	5	.....	III A
5424.85	5424.616	100	100R	50	10	II
5437.56	5437.393	4	10	5	.....	III A
5473.90	5473.689	3	10	4	.....	III A
5519.28	5519.115	200	150	70	20	II
5535.70	5535.534	1000R	1000R	500R	400	I
5593.50	5593.297	3	5	3	.....	III
5620.2	.....	4n	?	.....	.....	IV?
5620.6	.....	20n	?	.....	.....	IV?
5680.45†	5680.173	2	5	3	.....	III A
		10	20	10	.....	III A
5709.89	5709.546	2n	3	1	.....	III
5713.80	5713.554	4n	6	2	.....	III
5778.00	5777.695	400r	200R	70	20	II
5784.29	5784.105	4	6	2	.....	III
5800.60	5800.299	100	80	50	4	III
5805.92†	5805.712	20	30	40	8	II
5819.19	5818.906	5	20	12	.....	III A
5826.56	5826.294	150	125r	60	30	II
5853.91	5853.699	200	40	20	.....	III
5907.81	5907.656	15	30	20	10	II A
5962.7	5962.445	2	7	2	.....	III A
5965.00	5964.787	5	5	2	.....	III
5972.00	5971.715	100	80	60	50	II
5978.69	5978.496	4	10	6	.....	III A
5997.39	5997.102	100	80	60	40	II
6019.70	6019.505	100	90	60	40	II
6063.44	6063.149	200	125r	80	60	II
6083.67	6083.441	5	15	5	.....	III A
6111.10	6110.808	300r	200R	100	80	II
6129.50	6129.335	3	5	2	.....	III
6141.95	6141.760	600r	50	30	5	III
6235.5 †	.....	30n	20	6?	.....	III
6323.6 †	.....	3	5	?	.....	III?
6341.93	6341.697	150	100	100	80	I
6411.95	.....	4	20	10	.....	III A
6451.11	6450.842	125	100	100	80	I
6483.21	6482.936	200	125	100	60	II
6497.21	6496.902	600r	75	75	8	III
6499.10	6498.776	300r	300r	200	125	II
6527.60	6527.324	250	150	150	100	I
.....	6564.38 †	2	5	2?	.....	III A
6581.00	6580.77 †	6	10	4	.....	III

TABLE III—*Continued*

λ Exner and Haschek	λ Schmitz (I.A.)	Arc	Furnace			Class
			High Temperature	Medium Temperature	Low Temperature	
6595.65.....	6595.351	200	125	100	80	I
.....	6642.40 †	1n	3	?	.....	III A
6654.27.....	6654.120	10	15	4	.....	III
6675.50.....	6675.280	80	70	80	60	I
6694.08.....	6693.875	70	60	80	60	I

λ	Remarks
3158.	Very diffuse at high temperature.
3165.	Shaded to red at high temperature.
3184.	Appears as hazy patch in arc. Blend V in furnace.
3193.	Not resolved at high temperature.
3204.	Very hazy in arc.
3221.630.	Reduced in atmospheric furnace to one-third strength of λ 3222.188.
3222.	Very hazy in arc.
3222.441.	Shows in atmospheric furnace as shading to λ 3222.188.
3261.961.	Reduced in atmospheric furnace to two-thirds strength of λ 3262.336.
3262.336.	Unsymmetrically reversed at high temperature.
3281.772.	Fades to trace in atmospheric furnace.
3322.797.	Unsymmetrically reversed at high temperature.
3323.058.	Not visible as separate line in atmospheric furnace.
3357.	Unsymmetrical to red at high temperature.
3377.391.	Fades to one-tenth strength of λ 3376.975 in atmospheric furnace.
3421.008.	Fades to one-tenth strength of λ 3420.322 in atmospheric furnace.
3421.476.	Very faint and diffuse in atmospheric furnace.
3426.	Disturbed by band.
3464.	Hazy patch in arc. Faint and diffuse in atmospheric furnace.
3525.	Unsymmetrically reversed at high temperature.
3531.	Very hazy in arc. Resembles λ 3464.
3545, 3579, 3637.	Unsymmetrically reversed at high temperature.
3862.	Disturbed by band.
3945, 3947.	Very hazy in arc. Measured in vacuum furnace.
4026.	Disturbed by band.
4332.	Blend with V at high temperature. Probable intensity of V line subtracted.
4636–4663.	Disturbed by carbon.
4699.	Measured in vacuum furnace.
4732.	Disturbed by carbon.
4900.	High-temperature line may belong to carbon.
5055–5309.	Disturbed by band. Faint, if present in furnace.
5680.	Double, not fully resolved.
5805.	Very strong at medium temperature.
6235–6323.	Disturbed by band.
6564–6580.	Measured in vacuum furnace.
6642.	Shaded to red in arc. Measured in vacuum furnace.

a special measurement of these lines as produced by the furnace. These differences consist not merely in a sharpening of the lines, but, in several cases, of a resolution of diffuse arc lines into two

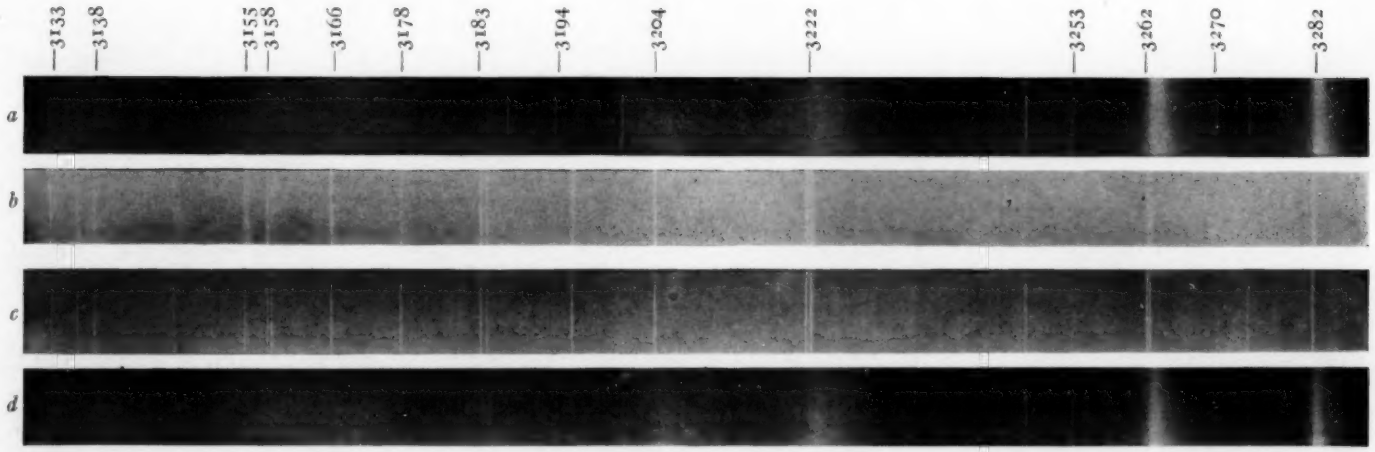
or three components in the furnace. For lines remaining single in both furnace and arc the dissymmetry almost disappears in the furnace spectrum, so that wave-lengths very nearly free from widening influence are obtained.

Photographs for the measurement of furnace lines were made in the second order of the 15-ft. concave grating spectrograph, the dispersion being 1 mm = 1.86 A. The furnace was operated at about 2000°, which gave very sharp lines, without the reversals combined with incipient dissymmetry which appeared at higher temperatures. Standard lines were obtained by mixing a small amount of iron with the barium in charging the furnace. As far as λ 3640, the wave-lengths on the international system in the second column of Table III were deduced from measurements of these plates, the mean of three complete sets being taken. For the iron lines the values of Burns[1] were used. Since the data on pressure-shift are scanty for this region, his wave-lengths, which are for the iron arc at atmospheric pressure, were used for the vacuum source without correction.

The different appearance of the furnace lines as compared with those of the arc in air is shown in Plates II and III. The arc spectra above and below, in each plate, were photographed alongside the furnace spectra at 2350° and 2000° respectively (spectra *b* and *c*), and the close coincidence of symmetrically reversed lines such as λ 3071 and λ 3501 in arc and furnace showed a freedom from instrumental displacement. The arc lines become more and more diffuse as the wave-length decreases until the lines to the violet of λ 3204, while they cannot be said to be absent, are so hazy as to be indistinguishable even on strong photographs. In the furnace they are well defined and fairly sharp and have been measured on the furnace plates. The other barium lines shown are so wide and unsymmetrical in the arc in air that only rough measurements are possible. Measurements of the furnace lines give not only a close value for the position of the unwidened line, but, in some cases, the wave-lengths of component lines whose presence is not indicated in the arc. This results from the fact that lines are frequently resolved into components which in the arc in air are

[1] *Lick Observatory Bulletin*, **8**, 27, 1913.

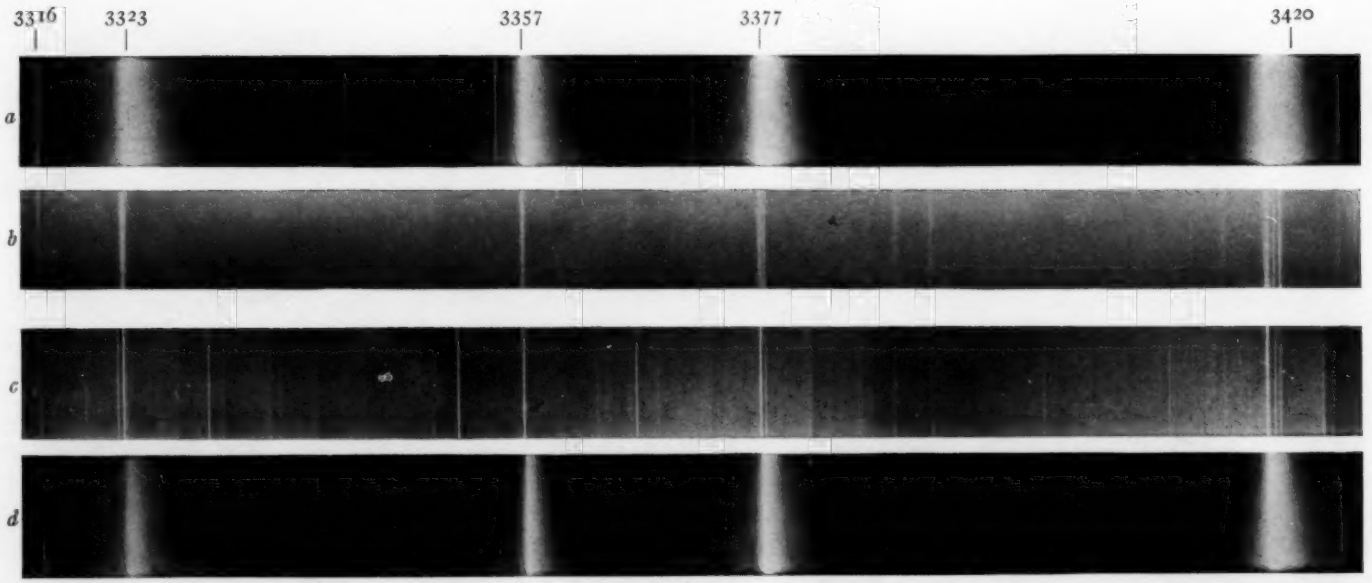
PLATE II



FURNACE AND ARC SPECTRA OF BARIUM

a, *d*. Arc spectrum at atmospheric pressure
b. Furnace spectrum at 2350°
c. Furnace spectrum at 2000°

PLATE III



FURNACE AND ARC SPECTRA OF BARIUM

a, *d*. Arc spectrum at atmospheric pressure
b. Furnace spectrum at 2350°
c. Furnace spectrum at 2000°

merely wide, unsymmetrical lines with no indication of structure. These components sometimes occur in pairs, as for λλ 3262, 3282, 3377, and sometimes with a third component as in the case of λ 3222 and λ 3420. The position of the chief component is at the extreme violet edge of the arc line; this is also the case when there is but one component, as, for example, with λ 3357. The extra components, when they occur toward the red, might be considered as blending into a shaded line in the arc, but both λ 3222 and λ 3262 show a component to the violet, where nothing appears in the arc. A violet component of λ 3323 is shown in Plate III*c*, but this is due to a strontium impurity.

The question arises as to whether this resolution into components is due solely to the low pressure in the furnace or in part to the absence of the discharge conditions of the arc. To test this, photographs were made at approximately the same temperature (2300°) with the furnace in vacuum and at atmospheric pressure, the results being compared with the spectrum of the arc in air. The results showed that the furnace at atmospheric pressure gives an intermediate spectrum to the extent that the extra lines characteristic of the vacuum furnace are weakened and an unsymmetrical widening of the principal components has commenced; but the use of atmospheric pressure has by no means changed the furnace structure into that of the arc. The distinctive features of the furnace lines, such as the violet components of λ 3222 and λ 3262, are still present.

Another method of making the furnace lines approach the structure given by the arc is to increase the temperature of the vacuum furnace with plenty of barium present. This, as may be seen from Plate III*b*, leaves the relative intensity of the furnace components almost unchanged from the condition at lower temperature (Plate III*c*), but produces an unsymmetrical reversal of the stronger lines. This dissymmetry evidently is a beginning of the strong one-sidedness shown by the arc lines.

The type of excitation occurring in the arc is thus chiefly responsible for the fading out of certain components and the strong dissymmetry shown by the arc lines in this region of the barium spectrum. Increase of pressure reinforces the widening action but

is only slightly effective in changing the intensity of the components of furnace lines.

Occurrence of barium lines in the solar spectrum.—That barium occurs in the solar atmosphere is rendered fairly certain by the strong arc pair λ 4554 and λ 4934, which correspond in each case with a close doublet in the solar spectrum. λ 5853.91 and λ 6141.95 also occur as strong solar lines. All of these lines are much weaker in the furnace than in the arc. Lines strong in both arc and furnace are faint in the sun, and often unidentified with barium by Rowland. Thus λ 5535.70, which dominates the furnace spectrum, if present in the sun, has an intensity of only 0. Other strong furnace lines are still fainter in the solar spectrum, the tendency being toward a weakening of those lines for whose appearance the furnace is especially favorable. Most of the ultra-violet lines of barium, strongly widened in the arc and reduced to sharp lines in the furnace, are of a type which should be present in the solar spectrum, though probably faint. It is of interest to examine some of the cases in which a wide arc line is replaced by two or three narrow lines in the furnace. Seven groups were taken, from λ 3183 to λ 3421, and their wave-lengths on the Rowland system were deduced from neighboring iron lines. In some cases the position of the barium line coincides with that of a stronger line of another substance, but when this is not the case a solar line of intensity from 00 to 0000 invariably appears close enough to the position of the furnace line to be within the error of measurement. There is thus considerable probability that the solar conditions are such as to produce a resolution of these lines into the components which occur in furnace spectra. Such conditions, according to present evidence, appear to be a moderately high temperature combined with low pressure in the region occupied by the barium vapor.

MAGNESIUM

The magnesium lines listed in Table IV show a great variety of types. The low-temperature spectrum consists of the triplet near λ 3830, the single line λ 4571, and the b group λλ 5167–84. λ 2852, while one of the strongest lines observed during the furnace investigations, is beyond the ultra-violet limit reached by photographs

of the low-temperature spectrum. λ 4571 is a low-temperature line of extreme type, in that it is decidedly weakened both in the furnace

TABLE IV

TEMPERATURE CLASSIFICATION OF MAGNESIUM LINES

λ Exner and Haschek	λ Nacken (I.A.)	Arc	Furnace			Class
			High Temperature	Medium Temperature	Low Temperature	
2733.7.....	2733.55	5n	1	.....	.....	IV
2736.8.....	2736.60	10n	2	.....	.....	IV
2776.82.....	2776.704	10	4	.....	.....	IV
2778.40.....	2778.289	10	4	.....	.....	IV
2779.95.....	2779.853	12	5	.....	.....	IV
2781.51.....	2781.431	10	4	.....	.....	IV
2783.08.....	2782.989	10	4	.....	.....	IV
2795.64.....	2795.545	60	10	.....	.....	IV
2802.82.....	2802.718	40	8	.....	.....	IV
2852.25†....	2852.128	300R	1000R	400R	.....	III
2937.00.....	2936.754	2	2	.....	.....	IV
2938.70.....	2938.487	4	4	1	.....	IV
2942.22.....	2942.016	8	8	2	.....	III
3091.20.....	3091.093	20	20	5	.....	III
3093.14.....	3093.011	40	40	12	.....	III
3097.08.....	3096.914	50	50	15	.....	III
3330.09.....	3329.934	10	10	5	.....	III
3332.31.....	3332.163	15	20	15	.....	III
3336.83.....	3336.688	20	30	20	.....	III
3829.51†....	3829.364	40	?	20	15	II
3832.49†....	3832.306	80r	?	40	30	II
3838.45†....	3838.283	100r	?	50	40	II
4059.15.....	4057.81	5n	3	1	.....	III
4167.8 †....	4167.65	10n	5?	?	.....	III?
4352.35.....	4351.940	30	?	1	.....	IV
4571.31†....	4571.114	5	?	80	80	I A
4703.40†....	4703.069	40	?	.....	.....	V
5167.50.....	5167.303	40	20	10	5	II
5172.87†....	5172.673	80	40	25	15	II
5183.78†....	5183.600	125	60	40	20	II
5528.70.....	5528.466	10	.....	.....	.....	V
5711.38.....	5711.127	1	.....	.....	.....	V

REMARKS

λ	
2852.	Line may attain enormous intensity in furnace. Reversals up to 30 A wide have been observed.
3829–3838.	Difficult at high temperature on account of λ 3883 band. Apparently not stronger than at medium temperature.
4167.	Disturbed by band.
4352.	Concealed by band at high temperature.
4571.	Very faint, if present at high temperature. Weakens as emission line; appears at 2500° as narrow absorption line.
4703.	Disturbed by band; very faint if present.
5172–5183.	Reversed at 2500°.

at high temperature and in the arc. It has not been possible to obtain this line strongly widened, as the conditions which give widening diminish its strength. At high temperature it is likely to appear as a narrow absorption line if the continuous background is strong enough. Its characteristics are very similar to those of λ 6573 of calcium, and, like that line, it is a good indicator of low temperature.

The furnace shows only faintly λ 4352 and λ 4703, both of which are strong in the arc and not enhanced in the spark. The enhanced line λ 4481 is not listed in Table IV, as it does not appear in the ordinary carbon arc containing magnesium. As would be expected, no trace of it is found in the furnace spectrum.

In the blue and green a series of spectrograms made in a previous investigation,[1] when hydrogen at pressure up to 20 cm was used in the furnace, were compared with spectra given by the vacuum furnace, but the hydrogen appeared to have no effect on the line spectrum.

SUMMARY

The foregoing pages summarize an investigation of the furnace spectra of calcium, strontium, barium, and magnesium from the standpoint of the lines appearing at each of three stages of temperature. The lines are classified according to the temperature at which they appear and their rate of change with increase of temperature. Special note is made of connection with series relations, of change of characteristic features of the furnace spectrum with the wave-length, and of differences of structure in furnace lines as compared with those of the arc. The differences of structure, in the case of barium, have led to the measurement of a number of ultraviolet lines not given in tables of arc wave-lengths.

MOUNT WILSON SOLAR OBSERVATORY
February 1918

[1] *Mt. Wilson Contr.*, No. 114; *Astrophysical Journal*, **43**, 341, 1916.

ON STELLAR EVOLUTION

By WILLIAM DUNCAN MacMILLAN

There are two questions at the present time which are of fundamental interest to astronomers and physicists. The first question is, What becomes of the enormous flood of energy which is poured forth so lavishly by the sun and by the stars? Does it travel unendingly through the depths of space until it strikes some material object, or does it not?

The second question is, What is the source of the enormous subatomic energies which have been revealed in recent years by the radioactive elements, and which by implication exist in all of the other elements?

In the first question we ask, What becomes of this energy? In the second, Where does this energy come from? Surely such a situation is not so embarrassing as it would be if we had but one of these questions, for an infinite source or an infinite sinkhole of energy is scarcely to be thought of. The two questions seem mutually to answer one another, and it seems reasonable to conjecture that the energy which disappears from the sun and stars into space reappears sooner or later in the subatomic energies of the atoms.

One may suppose that the physical universe is finite or that it is infinite, for it is not possible to verify either supposition. The idea that the physical universe is finite is doubtless repugnant to most minds that have dwelt upon the subject, and we therefore reject this supposition. The distribution of matter in space may be roughly uniform or it may be distinctly non-uniform. Again we are at liberty to make either supposition, for neither can be verified. But if we assume the universe to be infinite, then unless the distribution of stars is non-uniform of a special type the entire sky should glow with a brightness equal to that of the sun's disk. Certainly this would be true if radiant energy is not extinguished in its course through space.

It is quite possible to distribute infinitely many stars in such a manner that the total quantity of light received from them should be anything we please. For example, imagine a series of concentric spheres of radius 1, 2, 3, ... n, ... ; and on the surface of each sphere is placed a number of stars, the number being equal to the integral part of the square root of the radius of the sphere. If the amount of light received from the star on the first sphere be taken as unity, then the entire amount of light received from all of the stars would be less than $1+\frac{1}{2^{3/2}}+\frac{1}{3^{3/2}}+\frac{1}{4^{3/2}}+\frac{1}{5^{3/2}}+$ . . . . which is finite, but the number of stars in the system would be infinite. In any such distribution, however, the average stellar density approaches zero as the distance becomes sufficiently great. While such distributions of stars are possible, they seem so highly improbable that we reject them and seek some other explanation of the blackness of the night sky.

There is no recourse save in the hypothesis that radiant energy is extinguished in its course through space. If we assume that there is a uniform distribution of stars and that the stars are all alike, there should be four times as many stars in any given magnitude as in the magnitude next brighter. The actual star-counts, however, show that while this ratio is maintained between stars of magnitude one and magnitude two it falls off steadily until between magnitudes sixteen and seventeen the ratio is only 1.8 instead of 4. Is the decline in the number of stars due to the extinction of light in traversing these enormous distances? It is a simple matter to assume that a certain percentage of radiant energy is lost in traveling through space and to test the hypothesis by an appeal to the star counts. Obviously the stars do not all emit the same amount of light; that is, they are not all of the same absolute brightness. Thus the star AOe(N) 17,415 is only 0.004 times as bright as the sun, while Canopus cannot be less than 10,000 times as bright as the sun (absolute magnitudes, of course, being understood). Thus between the faintest known star and the brightest known star there is a ratio of 2,500,000 or sixteen magnitudes (absolute). Assuming that the stars are distributed over fourteen magnitudes (absolute) in accordance with the law of probability, and that 1 per cent of light

is extinguished in traveling 4.11 parsecs (13.6 light-years), the following table has been computed showing the number of stars of the various relative magnitudes on the hypothesis of uniform distribution of the stars in space. The actual star-counts of Chapman and Melotte of the Royal Observatory at Greenwich are given for comparison.

Mag.	Star-Counts	Computed	Mag.	Star-Counts	Computed
6.....	2,026	2,201	12.....	961,000	960,200
7.....	7,095	7,135	13.....	2,023,000	2,080,000
8.....	22,550	21,770	14.....	3,964,000	4,219,000
9.....	65,040	62,230	15.....	7,824,000	8,034,000
10.....	172,400	166,200	16.....	14,040,000	14,420,000
11.....	426,200	413,400	17.....	25,390,000	24,510,000

Certainly there is nothing in these figures to forbid us from supposing that the blackness of the sky is due to the extinction of light in its journey through space; and the amount of the loss (1 per cent in 13.6 years) does not seem excessive.

But what becomes of the energy which is lost? Is it permissible to suppose that the light is intercepted by dark material scattered through space? It is clear that the effectiveness of dark material in cutting off light is increased by supposing it in a finely divided state. If it is supposed that the dust of space consists of particles one one-hundredth of an inch in diameter it is found that one such particle to every 560 cubic miles of space would be sufficient to account for the 1 per cent of loss mentioned above. This does not seem to be an excessive amount of dust particles, and yet a continuation of the computation shows that in the 40 cubic parsecs which, according to the foregoing figures, is the sun's share of space, there is $6\frac{3}{4}$ times as much material as there is in the sun itself, and if the particles average one-tenth of an inch in diameter there is 67.5 times as much material as in the sun.

It may indeed be true that such dark material exists in space, but nevertheless it cannot account for the blackness of the sky, because the energy which it intercepts is either retained or radiated. If it is radiated, then there is no change in the total amount of radiation; at most merely a change of wave-length, since the

amount radiated is the same as the amount intercepted. So far as the total quantity of energy is concerned the result is the same as though the dark material were transparent. If the energy is retained, then the dark material would eventually become hot and would itself be bright. One concludes, therefore, that dark material in space cannot account for the blackness of the sky.

The accepted notion that radiant energy suffers no loss in transmission through a dust-free ether is not analogous to other physical processes, for in the physical world "perfection" does not seem to be attained. Perfection is an intellectual ideal, comfortable only so long as it represents the known facts with an approximation sufficient for our purposes. If we confine ourselves to a sufficiently small portion of the earth's surface we may be well satisfied with the hypothesis that the earth's surface is a plane, for the facts encountered are in close agreement with our hypothesis; but in a larger field of operations the curvature of the earth's surface is thrust upon us and cannot be ignored. So with the transmission of radiant energy it may be quite accurate enough to assume that there is no loss in such distances as are encountered in the solar system, but appreciably wrong when the distances encountered are of interstellar dimensions. According to Kapteyn the average distance of the first magnitude stars is 75 light-years. We have a right to be cautious in extending our hypothesis of "perfection" in the transmission of radiant energy into regions in which 75 light-years is the unit of distance.

If dark material seems inadequate to diminish the total amount of radiation, we may have recourse to the absorption of energy in the ether. But the energy cannot be absorbed without doing work, and in casting about for some sort of work which this lost energy might do there occurs the possibility that it is here that the foundations of the atoms are laid, and perhaps also the completed structure.

Let us assume that absorption does occur and attempt to construct a model to illustrate how the kinetic energy of the ether-waves might be converted into the potential energy of an organized system.[1]

[1] It is not essential, perhaps, to suppose that there is an ether. Some other process would answer our purpose; but it seems preferable to use the current concepts of physics.

Imagine a number of spheres floating on the surface of the ocean. Imagine further that on these spheres there are springs, and that at the bottom of each spring there is a hook. As these spheres are tossed about by the waves there will be frequent collisions, followed in general by an immediate separation. Occasionally, however, two spheres will collide in such a way that when the springs are compressed the hooks are engaged, and separation does not follow. The two spheres are locked in tight embrace, and we have the beginning of an organized system. The energy of the compressed springs was absorbed from the energy of the ocean waves, though the amount of energy absorbed was perhaps relatively small. The two spheres thus joined would, in the course of time, unite with other spheres, and thus an organized system would be built up and the internal energy of the system would have been derived from the ocean waves. It is not necessary, indeed, to dwell upon the details of such a process. Through the agency of chlorophyll it is known that the radiant energy of the sun is absorbed and locked up in the organized systems of the vegetable world, though the mechanical details of the process are quite unknown. In a manner analogous to the organic molecule, and by a process the details of which are quite unknown, we may suppose that the ordinary atom comes into being and that the familiar properties of inertia and gravitation are due to the energies locked up within. Disrupt the atom and set its energies completely free and the properties of mass and gravitation at once disappear.

Important consequences follow the admission that atoms are built up in this manner. It would follow that space contains much material of atomic or even molecular dimensions, and that regions long undisturbed by stellar objects would tend to become more or less crowded with atoms and molecules on account of the ceaseless passage of radiant energy through it. In this manner we see the genesis of a nebula with its enormous gravitational and subatomic energies. A sufficiently large mass in its journey through space would gather in this atomic and molecular material and feed upon its substance and energies. It would be a nucleus around which material would gather. If this nucleus were relatively small and dark, such as the earth, its growth would be slow; the

subatomic energies would persist as subatomic energies, and the mass would increase. In the course of time the internal pressure, density, and temperature would increase, and one can imagine that a critical situation would eventually be reached in which the subatomic energies can no longer wholly persist as subatomic. The atoms begin to break down and give up their stores of energy. In the event of a complete dissolution of the atom we would expect the complete disappearance of its mass and a complete restitution of the energy by which it was organized. If the dissolution were but partial we would have the familiar radioactive phenomena and a partial restitution of the subatomic energies. The energies thus released would raise the temperature of the nucleus and presumably hasten the process of disintegration. The density would decrease until, if the mass were large enough, the increased molecular energies would convert the once solid nucleus into a gaseous sphere. If the mass continued to grow after a completely gaseous state had been reached, the increased gravitational pressure would cause the density again to increase, and this increase with a growing mass would continue until eventually again a critical state would be reached of heat and pressure, and the release of subatomic energies would be so great that the gaseous mass would begin to glow. A further increase of mass would again hasten the process of dissolution accompanied by a rise in temperature and a second decrease in density, and the process could continue, as far as we can see, until the tenuity of a nebula was attained. If the various bodies in our own solar system, with whose masses and densities we are familiar, be arranged according to their masses, it is found that they do conform to these ideas, as is shown in the diagram (Fig. 1). Thus all of the planets and satellites which are smaller than the earth are in a solid state and their densities increase with an increase of mass. Somewhere between the mass of the earth and the mass of Uranus, which is fourteen times the mass of the earth, there would exist a mass of maximum density beyond which a solid mass cannot persist as wholly solid, and there begins a transitional state between the solid and the wholly gaseous condition, and in this transitional state we find the planets Uranus and Neptune. Saturn, with a mass equal to 94 times the mass of the earth, seems to

have attained a wholly gaseous condition and has the smallest density of any object in the solar system. The mass of Jupiter is 3.3 times the mass of Saturn and its density is about twice that of Saturn. There are no bodies in our solar system intermediate between Jupiter and the sun, but it is not difficult to imagine that somewhere in between the increased mass and increased density would again produce an internal condition in which the production of heat would be so great that the mass would begin to glow and that relief from this state of excessive energy would be found in a decreased density. Thus the sun, which is in the very midst of stellar conditions, has a density but little in excess of that of Jupiter notwithstanding its enormous mass.

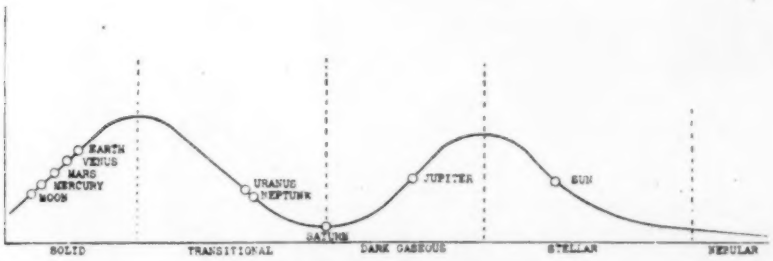


FIG. 1.—Density as a function of mass

When the stellar condition had been reached by a growing gaseous mass, the radiation of its energies into space would afford relief to the imprisoned atoms, tending to check the disintegrating process. Eventually there would be an equilibrium between the energies furnished by the process of dissolution and the energies expended in radiation and gaseous expansion against gravitation. If the process of gathering up atomic and other material from space were discontinued, the mass of the star would diminish, its volume would shrink, and its density would increase. The temperature eventually would fall and the critical state would be passed again, but this time in the direction of a return to the pre-star state. There would be relief from the excessive pressure and temperature which had brought about the release of subatomic energies, and a return to the dark state would be possible.

It is not necessary, however, to suppose that the ingathering process is stopped. If it continued at a suitable constant rate an equilibrium would be attained between the income and outgo of energy, the energies of radiation would be continued, the mass would remain constant, and it would endure as a star forever. If in its wanderings the star passed through a region unusually rich in material, its mass again would grow and its temperature would rise until it attained the white brilliancy of star of spectral type A or B or in the extreme case pass into the nebular state, in which the internal energies are gravitational-potential rather than the kinetic energies of heat. If it is assumed, as is natural, that in such a vigorous process of dissolution there would be a large residue of hydrogen and helium, we can account for the peculiar character of the spectra of stars of these types, for, owing to the lightness of these gases, they would rise to the surface and form an extensive envelope surrounding the brilliant star itself.

In this connection W. W. Campbell has made the following observations:[1]

> The class B stars and the stars containing bright lines are where the planetary and irregular nebulae exist. Going further into detail: wherever there is a great nebulous region either in or near, or outside of the Milky Way you will find the class B and earlier types of stars abnormally plentiful; and the chances are fairly strong that some of the stellar spectra will contain bright lines. This is true of great regions in the Milky Way; it is true of the Orion and Pleiades regions, which we see at some distance outside of the Milky Way structure, though they are doubtless within our system. If you see a wisp of nebulosity near a bright star, look up the star's spectrum and you will probably find it an early class B, as in the case of Gamma Cassiopeiae, a second-magnitude star, with nebulous structure near it whose spectrum contains both dark and bright lines of hydrogen and helium. If you see an isolated bright star enmeshed in an isolated patch of nebulosity, such as the one shown in Fig. 37, and the books say the star (BD–10°4713) is yellow, or of class G, communicate your suspicions that the books are mistaken about the star's spectrum to Professor Pickering, and he will probably reply that the star is in reality a very blue one of early class B. That is what happened a fortnight ago about this particular nebula and the star near its apparent center. If you find a red or yellow star of normal type do not look for a nebula in apparent contact with it. Nebulae and red stars do not coexist. You will find about

[1] "Address of the Retiring President of the American Association for the Advancement of Science," *Science*, **45**, 545, 1917.

the same number of red stars in the Milky Way that are visible in similar areas far from the Milky Way. You will find an occasional red star in the region of the Orion nebula and of other large nebulae, but the red stars will not appear there in greater numbers than their approximately uniform distribution over the sky requires.

The connection between the nebulae and the bright line stars and between nebulae and the early class B stars is close, both as to their types of spectra and as to their geometric distribution.

Just as the kinetic theory of gases shows that there is a lower limit to the mass of a planet which can retain an atmosphere, so the present considerations suggest a lower limit of mass to a star which can emit light, and possibly also an upper limit to the mass of a star beyond which the star passes into a nebula. An exact correlation between the mass of a star and the intensity of its radiation would be expected only for those stars in which there was equilibrium between the energies released and the energies radiated. A star growing in mass with relative rapidity might lag in temperature, owing to a possible time element in the release of subatomic energies; and likewise a star decreasing in mass might remain for a long period relatively too hot. But on the whole one would expect an increase in temperature with an increase of mass until the kinetic energy of the molecules became so great that the star tended to pass from the gaseous to the nebulous stage. This would mean a decline in internal pressure and in radiation, although the internal energies, increasingly of the potential form, were exceedingly great. The increase in the mean free path of the molecules and the decline in internal pressure would tend to check the release of subatomic energy, and in the extreme nebular state this release may virtually cease. In this manner one is led to imagine a maximum mass beyond which a star, as such, cannot exist. If nebular radiation be left out of consideration, a maximum of stellar mass would imply that there exists a maximum of stellar radiation. Although different stars vary enormously in the amount of their *radiations* their variations in *mass* are not excessive, at least if we may judge from the few masses which are definitely known.

If in its early stellar stage a star is of red color, one would expect to find a class of red stars of relatively small mass, viz., those masses which have been slowly growing toward starhood. On the other

hand, stars which are condensing from a nebula of large mass would present a class of red stars of large mass. The kinetic theory of gases would lead us to doubt the possibility of a nebula of small mass, or a nebula of very low density, even though the mass be large, ever condensing into a star through its own gravitational attraction. Thus, *if all the mass* in the solar system were a spherical nebula 10 times as large as the orbit of Neptune, its velocity of escape would be less than the velocity of escape on the moon, and it is well known that the moon cannot retain an atmosphere. It would seem that such a nebula would dissipate rather than concentrate. A third class of red stars would be those which were approaching extinction or passing into the dark gaseous state. If the main source of stellar radiation is the subatomic energy,[1] and if these energies are completely given up so that the atomic mass disappears, then one would expect those stars which are approaching extinction to be of small mass. If the various chemical elements have different critical conditions of temperature and pressure for the release of their subatomic energies, the mass of a fading star would depend upon its chemical constitution, and so also would the mass of a young star. While this variation of composition would permit a variation in the mass of such stars, on the whole one would expect them to be small and of high density. One would expect, further, red stars of small mass to show considerable variability in their luminosity, owing to the cataclysmic nature of the process of changing from one physical state to another. These anticipations with respect to the red stars are quite in harmony with our present knowledge of this class of stars.

It is natural to suppose that atoms which are formed by the flow of energy through space would have little or no velocity at the time of their formation, and that the recently formed, irregular nebulae would have low velocities. On the other hand, nuclei of stellar types which have long been of stationary or of decreasing mass would have relatively high velocities, owing to the differential

[1] According to the hypothesis of the present paper the energy, or heat, obtained from gravitational contraction is merely energy which has been absorbed from the star itself on some previous occasion during a process of expansion against gravitation. In the long run no energy is obtained from this source, though it serves admirably as a reservoir of energy which can be drawn upon during times of famine.

gravitation of all the stars exerted over enormous periods of time. During the process of its growth, however, a star would be increasing its mass without increasing its momentum, since the momentum of the added material would be approximately zero, and therefore its velocity would be decreasing. If the surmise that a growing mass means an increase in the rate of the release of subatomic energy is correct, then the growing star would push its way through the various spectral types toward class B with an ever-decreasing speed, which is quite in harmony with our knowledge that stars of class B have low velocities and that higher velocities are associated with the stars of deeper color. It harmonizes also with the knowledge that the stars of class B are on the whole the massive stars.

So also a star of class B which was produced from a recently formed nebula would have a low velocity, and this velocity would increase through the ages, owing to the gravitational action of other stars. But in the meantime, as it radiated away its energies and decreased in mass its spectral type would change in the direction from B toward M, so that again there would be an association of the deeper colors with higher velocities. Obviously, the same star may at one time be increasing in mass and decreasing in speed, and at another be decreasing in mass and increasing in speed, the spectral type changing correspondingly, and these changes may be repeated indefinitely. In view of these possibilities, then, we cannot assign an upper limit to the duration of the life of a star; nor indeed could we say that a star has but one life, for it is quite conceivable that its life may be extinguished and renewed many times.

One can imagine that a wandering star finds its way into a nebula of sufficiently enormous expanse and has its velocity so decreased that it is unable to escape. Another star, and still another, is entangled in its filmy substance, and finally a whole group of stars are brought to rest within its borders. If these stars come from all directions at random, the moment of momentum of the group would be small. Since the moment of momentum of the nebula itself would be small, there would be little tendency for the system as a whole to rotate, but under their mutual attractions these stars would take the form of a globular cluster. In

the course of time they would sweep up the nebulous material which had bound them together; and this material for many ages would furnish the energy for their lavish radiation. But eventually it would be exhausted and the stars would decline in mass. As they did so, the gravitational control of the group on the individual members would be relaxed. The cluster would expand, and finally, one by one, the stars would escape and pursue their lonely journeys in search of new adventures.

An unusual epoch in the existence of a star will occur when it happens to pass through the immediate neighborhood of another star, an event which is almost certain to occur in a sufficiently extended period of time. The results of such an encounter are studied in the well-known researches of Chamberlin and Moulton on the planetesimal hypothesis of the development of our own planetary system. In this hypothesis the fundamental assumption is that at some remote epoch in the past our sun, even at that time a star, passed close by another star and that our planetary system has grown up and developed from the material which was torn from the sun by the tidal and disruptive action of the second sun. If the life of our sun is limited to some such period as a thousand millions of years it must be admitted that the chance for its encounter with another sun during this relatively short interval is small, and this objection has been urged. But if the time limit on the duration of the sun's life be removed, such an encounter becomes very probable, indeed almost a certainty, and our confidence in the planetesimal hypothesis is strengthened, or, perhaps better, our skepticism is somewhat weakened.

But if the sun is living upon material which is drawn in from surrounding space, the planets, too, at a smaller rate, must be adding to their masses and therefore growing, since they have not yet reached a stellar condition. In the course of time they too will grow to the full stature of a sun unless in the meantime the mutual perturbations of the planets shall have brought about the destruction of one or more of them through collisions among themselves or with the sun. Obviously the growth of the planets in such a manner would result in greatly contracting the dimensions of the planetary orbits, not only through the gravitative effect of increased

mass, but also because the ingathering process would have much the same effect as friction, since the process would add nothing to the momentum of the planets and would therefore decrease their speeds. It seems quite likely that the road to stellar condition would not be traveled very far before the terrestrial planets would be swallowed up by the sun, and, if the sun also were growing, by the time it had arrived at spectral type B the sun and Jupiter only would be left to form a binary star of short period—a typical type B binary. At the present time Jupiter is too small in mass to be a star. If the sun is now passing through a period in which its mass is decreasing, the mass of Jupiter will be growing, or at the very worst will be stationary, and therefore gaining relatively to the sun. One can fancy the sun decreasing toward extinction while Jupiter is slowly growing toward stellar conditions. In this manner Jupiter and the sun might approach equality in mass. At a later time, if the solar system passed through a region rich in matter the sun and Jupiter would grow equally, and our solar system, if not reduced to two members, at least would present the interesting phenomenon of a system of two dominating suns of approximate equality. In the early stages of this rejuvenation the sun and Jupiter would form a binary star of long period and reddish color. As they grew in mass gathered from surrounding space their colors would brighten, they would draw closer together, and their period would shorten. Since the effect of a resisting medium is to make the orbits circular, it can be shown that the product of the period and the fifth power of the sum of their masses would remain constant during this process of growth, and so also would the product of the mean distance and the cube of the sum of the masses remain constant. In other words, the period would vary inversely as the fifth power of the sum of the masses, and the mean distance inversely as the cube of the sum of the masses. If the masses of the sun and Jupiter were increased by gathering in atomic material to five times their present masses, the distance of Jupiter would be reduced from 500,000,000 miles to 4,000,000 miles, and its period would be reduced from about twelve years to approximately thirty-three hours. If the masses were of approximate equality their spectra would change in the direction from type M toward type B, and if

their masses were sufficiently great to have a spectrum of type B we should certainly have a short-period binary with the circular orbit which is characteristic of this class of spectroscopic binaries. On the other hand, if we follow such a binary in our imaginations as through the ages it decreases in mass, we see the reverse process taking place, the distance between the stars increasing and the eccentricity increasing likewise, but the temperature decreasing and the color tending through the yellow toward the red until we see finally a typical visual binary.

An indefinite prolongation of a star's life undoubtedly would vastly increase the significance to be attached to a close approach of two stars, since such a close approach is merely a matter of sufficient time. With the relatively short span of life hitherto assigned to a star such an event is highly improbable until many aeons after the star has become cold and dead. The approach of two cold and solid stars would certainly have to be extremely close to have any further effect on the stars than to change their speeds and their paths, and it is very doubtful if anything short of actual collision would disrupt them. A quite different state of affairs would arise, however, if the stars were massive, and very hot and active. These are the conditions postulated in the planetesimal hypothesis, and the consequences of such conditions must play a very common rôle in the life-history of the stars. From the consequences in the sun-Jupiter system, in which it has been shown how Jupiter might become as massive as the sun and the sun become a binary star, a possible mode of genesis of these interesting objects is obtained. An extension of the planetesimal hypothesis seems quite competent to account for the existence of many binary stars, from the typical yellow, visual binaries of high eccentricity and long period to the typically short-period, white binaries of spectral type B with their almost perfectly circular orbits. The coalescence of the many members of a planetary system into a system of two or three members would furnish many occasions for the flashing up of a star into an intense but temporary brilliance, such as is exhibited in the relatively frequent temporary stars. It is not necessary, however, to suppose that all binaries are formed in the same manner, for it is quite conceivable that if a nebula has two centers of con-

densation a binary of long period and high eccentricity should result through the process of condensation. It is quite possible too that there exist other processes which have not yet been formulated.

Two processes are here recognized by which a star comes into existence. The first is a *possible* condensation from a nebula, though this does not seem to be as inevitable a process as it has generally been regarded. The second is the growth of a nucleus—a fragment perhaps from some disrupted mass, a witness of some titanic cataclysm—by the accretion of atoms and small particles to such a mass that the release of subatomic energies transforms it into a radiating star. By collision, or *very* close approach, only can we account for a star passing out of existence, in the first of which two masses are united into a single one, and in the second a single solid mass is disrupted into many fragments. But during the continuance of its existence a star is essentially a singular point in an infinite field of energy. Through these singular points the energy ebbs and flows. When the flow exceeds the ebb the star grows in mass and radiating power and character of spectrum. When the ebb exceeds the flow the star declines in mass and radiation, at times even to the point of extinction. But even during the period when its radiation fails, the singular point persists, and through it again flows the tide of energy when the conditions are suitable. Just as the atom and the molecule are permanent forms of physical existence, so also is the star a permanent form of physical existence, notwithstanding that the individual may pass from birth to its dissolution. There is no necessary limit to its age, and though the star itself may rise and fall, the universe as a whole is not essentially altered. The singular points may change their positions and their brilliancy, but it is not necessary to suppose that the universe as a whole has ever been or ever will be essentially different from what it is today.

UNIVERSITY OF CHICAGO
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ON SOME PHENOMENA OBSERVED IN THE FOUCAULT TEST

By SUDHANSUKUMAR BANERJI

The "knife-edge" test introduced by Foucault is one of the best-known methods for examining the performance of an optical surface.[1] Lord Rayleigh has recently published a paper dealing with the theory of this test, taking into account the part played by the diffraction of the rays reaching the focal plane.[2] In the present note I propose to describe some new phenomena that I have observed in the Foucault test, and to explain the results obtained in the light of the theory given by Lord Rayleigh. The case most readily admitting of mathematical treatment and which is the one considered in Lord Rayleigh's paper is that in which the surface under test is bounded by parallel straight edges and the knife-edge used is also placed parallel to these edges at or near the focal plane, the source of light being a fine slit parallel to the boundaries of the surface and to the knife-edge. My own observations have also been made with a similar arrangement.

It has long been known that when the illumination of the surface under observation is cut off by the advancing knife-edge in the focal plane, the edges of the surface remain bright and in fact shine out with enhanced brilliancy. This effect has long been known to be due to diffraction[3] and has been discussed in Lord Rayleigh's paper. There is another effect due to diffraction observed in Foucault's test which does not appear to have been previously recorded or explained. I have found that as the knife-edge is gradually advanced in the focal plane, the surface lying between the boundaries does not continuously decrease in brightness but

[1] See for instance the memoirs by Draper and Ritchey on the construction of a silvered glass telescope, *Smithsonian Contributions to Knowledge*, **34**, 1904.

[2] "On Methods for Detecting Small Optical Retardations, and on the Theory of Foucault's Test," *Phil. Mag.*, **33**, 161, 1917. See also a note by the present author in *Nature*, **99**, 206, 1917.

[3] See p. 32 in Ritchey's memoir quoted above.

that the illumination of the entire surface undergoes large fluctuations, becoming alternately greater or less, finally tending, however, to zero when the knife-edge is advanced considerably. With white light some very remarkable color-effects may be noticed. It is found that the boundaries of the surface appear luminous and white, but the region inside the boundaries shows color, this being practically of the same tint throughout, but most marked midway between the boundaries. The whole of the field between the boundaries passes through an interesting succession of colors as the knife-edge is slowly moved in the focal plane. The field outside the boundaries also shows a color (though much less vividly) which is in general complementary to that observed between the boundaries. These color-effects are obviously due to the fluctuations of the intensity of the entire field between the boundaries, not being in the same phase for different parts of the spectrum.

The theory of Foucault's test as developed by Lord Rayleigh is found to be capable of explaining these remarkable color-phenomena. The expression given by Lord Rayleigh for the intensity of the field as viewed in the direction ϕ is

$$I=\left[\mathrm{Si}\left\{\frac{2\pi}{\lambda}\theta\left(1+\frac{\phi}{\theta}\right)\xi_2\right\}-\mathrm{Si}\left\{\frac{2\pi}{\lambda}\theta\left(1+\frac{\phi}{\theta}\right)\xi_1\right\}\right.$$
$$\left.+\mathrm{Si}\left\{\frac{2\pi}{\lambda}\theta\left(1-\frac{\phi}{\theta}\right)\xi_2\right\}-\mathrm{Si}\left\{\frac{2\pi}{\lambda}\theta\left(1-\frac{\phi}{\theta}\right)\xi_1\right\}\right]^2$$
$$+\left[\mathrm{Ci}\left\{\frac{2\pi}{\lambda}\theta\left(1-\frac{\phi}{\theta}\right)\xi_2\right\}-\mathrm{Ci}\left\{\frac{2\pi}{\lambda}\theta\left(1-\frac{\phi}{\theta}\right)\xi_1\right\}\right.$$
$$\left.-\mathrm{Ci}\left\{\frac{2\pi}{\lambda}\theta\left(1+\frac{\phi}{\theta}\right)\xi_2\right\}+\mathrm{Ci}\left\{\frac{2\pi}{\lambda}\theta\left(1+\frac{\phi}{\theta}\right)\xi_1\right\}\right]^2,$$

where ξ_1, ξ_2 are the limits of the aperture in the focal plane and θ is the angular semi-aperture of the lens under test. In practice ξ_2 is large. To illustrate the fact that the luminosity of the field between the boundaries undergoes fluctuations as ξ_1 is gradually increased, I have prepared Table I showing the intensity of different points of the field as calculated from the expression given above, taking $\xi_2=\frac{300\lambda}{2\pi\theta}$ and $\xi_1=\frac{3\lambda}{2\pi\theta}x$, where x has the values 1, 1.63, 2,

2.62, and 3 in succession, these being approximately the values for which the intensity at the center of the field is greatest or least.

It will be seen from the figures in Table I that the intensity of the entire field between the limits $\phi/\theta = \pm 1$ becomes alternately greater and less as ξ_1 is increased. This fact is not brought out in Rayleigh's paper. The region outside the boundaries does not show such a marked variation. In fact, observation shows that when ξ_2 is large a variation of ξ_1 produces a relatively insignificant effect on the intensity of the field outside the boundaries. If, however, ξ_2 be not large, experiment and theory agree in showing that a variation of either ξ_1 alone or of both ξ_1 and ξ_2 ($\xi_2 - \xi_1$ remaining constant) results in a marked fluctuation of the intensity of the

TABLE I

x	Values of ϕ/θ												
	0	±.1	±.2	±.3	±.5	±.8	±.9	±1	±1.1	±1.2	±1.5	±1.8	±2
1.....	0.31	0.34	0.320	0.350	0.472	1.015	1.310	20.23	1.685	0.755	0.174	0.071	0.038
1.63...	0	.0001	.005	.020	.063	.299	1.330	16.82	1.601	.621	.197	.087	.060
2.....	.09	.07	.083	.095	.147	.395	1.009	15.30	.837	.328	.052	.019	.035
2.62...	0	.0009	.002	.007	.006	.153	.604	13.73	.727	.235	.042	.013	.015
3.....	.01	.033	.032	.038	.019	.178	.544	12.35	.544	.178	.040	.032	.012

field outside the boundaries, and the colors observed in this region with white light become more prominent. It should be remarked here that when ξ_2 is not large the regions inside and outside the boundaries (observed in white light) are not generally of uniform tint throughout, as diffraction fringes appear showing a regular succession of colors, although a preponderance of a particular color within the boundaries and of a complementary color in the region outside may be noticed. As the knife-edge is moved in, the relative intensities of the different colors change to an enormous extent, and the positions of the different fringes shift to and fro. The changes in the position and the color of the bands within the boundaries are most interesting to watch when their number is small. If it is arranged to alter both ξ_1 and ξ_2 ($\xi_2 - \xi_1$ remaining constant and small), a fluctuation in the number of the fringes

between the boundaries from one to two, or two to three, and vice versa, may be observed, these changes being accompanied by a fluctuation in the intensity of the bands. As an illustration of this I have calculated the distribution of intensity from Lord Rayleigh's expression for two sets of values of ξ_2, ξ_1, these being $\xi_2 = 0.7$ mm and $\xi_1 = 0.5$ mm, and $\xi_2 = 0.8$ mm and $\xi_1 = 0.6$ mm, and $\frac{2\pi\theta}{\lambda}$ was taken to be $30x(\text{mm})^{-1}$. The intensity-curves have been plotted in Figs. 1 and 2.

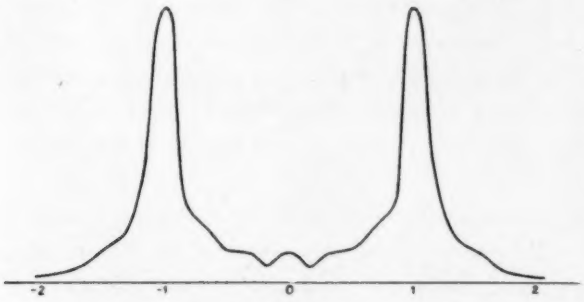

FIG. 1

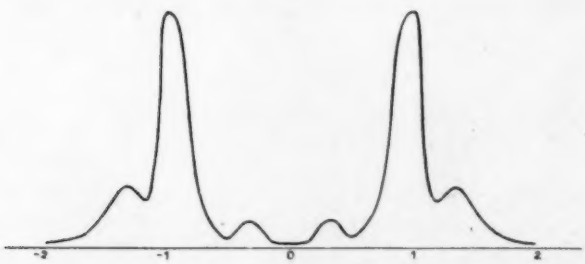

FIG. 2

PHENOMENA OBSERVED WHEN THE KNIFE-EDGE IS NOT IN THE FOCAL PLANE

Lord Rayleigh has confined himself in his paper to the case in which the knife-edge is put exactly in the focal plane. In the practical application of the Foucault test, the position of the focal plane has to be found by actual trial, and it is therefore of interest

to consider also the effects observed when the knife-edge is put in a plane a little in advance of or behind the focal plane. Actual experimental observation in the case of a rectilinear boundary under these conditions shows that when the knife-edge is sufficiently advanced so as to cut off the general illumination of the surface, the two edges of the field still appear luminous *but differ markedly in their brilliancy*. This difference becomes greater and greater as the knife-edge is put in a plane farther and farther from the focus. The effect is reversed if the knife-edge is put in front of instead of behind the focal plane, and has no doubt been frequently noticed by those who have applied Foucault's test in practice. It should be remarked also that when the knife-edge is considerably advanced in any given plane the inequality of the luminosity of the two edges diminishes. The mathematical theory of these effects is given below.

Let A represent the lens with its rectangular aperture which brings parallel rays to a focus O. Let a screen containing an aperture parallel to the aperture of the lens be placed at a distance a in advance of the focus. A is the center of the first aperture and Q any point on it, so that $AQ=s$. If P be any point on the second aperture and B the center of the screen, then putting $BP=\xi$ and $AO=f$, we get

$$PQ^2=QO^2+OP^2-2QO\cdot OP\cos POQ$$

$$=f^2+a^2+\xi^2+2f\cdot\sqrt{a^2+\xi^2}\cos\left(\frac{s}{f}+\tan^{-1}\frac{\xi}{a}\right)$$

$$=(f+\sqrt{a^2+\xi^2})^2-4f\cdot\sqrt{a^2+\xi^2}\sin^2\tfrac{1}{2}\left(\frac{s}{f}+\tan^{-1}\frac{\xi}{a}\right)$$

Since $\sin^2\frac{1}{2}\left(\frac{s}{f}+\tan^{-1}\frac{\xi}{a}\right)$ is small, provided ξ/a is small, we have, extracting the square root,

$$PQ=f+\sqrt{a^2+\xi^2}-\frac{2f\cdot\sqrt{a^2+\xi^2}}{f+\sqrt{a^2+\xi^2}}\sin^2\tfrac{1}{2}\left(\frac{s}{f}+\tan^{-1}\frac{\xi}{a}\right).$$

Now, since ξ/a is supposed to be small, we get

$$PQ=f+\sqrt{a^2+\xi^2}-\frac{f\sqrt{a^2+\xi^2}\cdot\xi^2}{2(f+\sqrt{a^2+\xi^2})a^2}-\frac{\xi\sqrt{a^2+\xi^2}}{a(f+\sqrt{a^2+\xi^2})}\cdot s-\frac{\sqrt{a^2+\xi^2}}{2f(f+\sqrt{a^2+\xi^2})}\cdot s^2.$$

Thus we see that

$$PQ=f+A+Bs+Cs^2$$

where

$$A=\sqrt{a^2+\xi^2}-\frac{\sqrt{a^2+\xi^2}\cdot f\xi^2}{2(f+\sqrt{a^2+\xi^2})a^2},$$

$$B=-\frac{\xi}{a}\cdot\frac{\sqrt{a^2+\xi^2}}{f+\sqrt{a^2+\xi^2}},$$

$$C=-\frac{\sqrt{a^2+\xi^2}}{2f\cdot(f+\sqrt{a^2+\xi^2})}.$$

Therefore the disturbance at the point ξ of the second aperture will be represented by

$$\int_{-s}^{s}\cos 2\pi\left(\frac{t}{T}-\frac{f+A+Bs+Cs^2}{\lambda}\right)ds.$$

If T be written for $\left(\frac{t}{T}-\frac{f}{\lambda}\right)\lambda$, the foregoing integral can be written in the form

$$\sin 2\frac{\pi}{\lambda}T\int_{-s}^{s}\sin 2\pi\frac{A+Bs+Cs^2}{\lambda}ds+\cos\frac{2\pi}{\lambda}T\int_{-s}^{s}\cos 2\pi\left(\frac{A+Bs+Cs^2}{\lambda}\right)ds.$$

The rays from the various points of the second aperture may be regarded as a parallel pencil inclined to the axis at a small angle ϕ.

When we proceed to inquire what is to be observed at an angle ϕ, we have to consider the expression

$$\cos kT \int_{\xi_1}^{\xi_2}\int_{-s}^{s} \cos k(A+Bs+Cs^2-\phi\xi)dsd\xi + \sin kT \int_{\xi_1}^{\xi_2}\int_{-s}^{s} \sin k(A+Bs+Cs^2-\phi\xi)dsd\xi,$$

where $K=\frac{2\pi}{\lambda}$ and ξ_1, ξ_2 define the limits of the second aperture.

The intensity I represented as the sum of the squares of the integrals is given by

$$I=\left[\int_{\xi_1}^{\xi_2}\int_{-s}^{s} \cos k(A+Bs+Cs^2-\phi\xi)dsd\xi\right]^2 + \left[\int_{\xi_1}^{\xi_2}\int_{-s}^{s} \sin k(A+Bs+Cs^2-\phi\xi)dsd\xi\right]^2.$$

The integration can be carried out with respect to s on putting $s=z-\alpha$ and choosing α so that the term containing the first power of z in the expression $A+B(z-\alpha)+C(z-\alpha)^2-\phi\xi$ vanishes. The integrals are thus reduced to integrals of the Fresnel class and can be integrated in semi-convergent series. Since K is a large quantity, we retain only a few terms of the series, and the subsequent integration with respect to ξ is effected by integrating by parts.

We thus find that the intensity is proportional to the sum of the squares of the expressions (I) and (II) given below.

(I)

$$\frac{c_2}{2C_2k}\Big[-\cos k(A_2+B_2s+C_2s^2-\phi\xi_2)\cdot s\Big]_{-s}^{s} + \left\{a_2-\left(b_2-\frac{B_2c_2}{2C_2}\right)\frac{B_2}{2C_2}\right\}\left[-\frac{\cos k(A_2+B_2s+C_2s^2-\phi\xi_2)}{k(B_2+2C_2s)}\right]_{-s}^{s} + \left(b_2-\frac{B_2c_2}{2C_2}\right)\frac{1}{C_2k}\Big[-\cos k(A_2+B_2s+C_2s^2-\phi\xi_2)\Big]_{-s}^{s}$$

$$-\frac{c_1}{2C_1k}\Big[-\cos k(A_1+B_1s+C_1s^2-\phi\xi_1)\cdot s\Big]_{-s}^{s}$$
$$-\Big\{a_1-\Big(b_1-\frac{B_1C_1}{2C_1}\Big)\frac{B_1}{2C_1}\Big\}\Big[-\frac{\cos k(A_1+B_1s+C_1s^2-\phi\xi_1)}{k(B_1+2C_1s)}\Big]_{-s}^{s}$$
$$-\Big(b_1-\frac{B_1C_1}{2C_1}\Big)\frac{1}{2C_1k}\Big[-\cos k(A_1+B_1s+C_1s^2-\phi\xi_1)\Big]_{-s}^{s}$$

(II)

$$-\frac{c_2}{2C_2k}\Big[\sin k(A_2+B_2s+C_2s^2-\phi\xi_2)\cdot s\Big]_{-s}^{s}$$
$$-\Big\{a_2-\Big(b_2-\frac{B_2C_2}{2C_2}\Big)\frac{B_2}{2C_2}\Big\}\Big[\frac{\sin k(A_2+B_2s+C_2s^2-\phi\xi_2)}{k(B_2+2C_2s)}\Big]_{-s}^{s}$$
$$-\Big(b_2-\frac{B_2C_2}{2C_2}\Big)\frac{1}{2C_2k}\Big[\sin k(A_2+B_2s+C_2s^2-\phi\xi_2)\Big]_{-s}^{s}$$
$$+\frac{C_1}{2C_1k}\Big[\sin k(A_1+B_1s+C_1s^2-\phi\xi_1)\Big]_{-s}^{s}$$
$$+\Big\{a_1-\Big(b_1-\frac{B_1C_1}{2C_1}\Big)\frac{B_1}{2C_1}\Big\}\Big[\frac{\sin k(A_1+B_1s+C_1s^2-\phi\xi_1)}{k(B_1+2C_1s)}\Big]_{-s}^{s}$$
$$+\Big(b_1-\frac{B_1C_1}{2C_1}\Big)\frac{1}{C_1k}\Big[\sin k(A_1+B_1s+C_1s^2-\phi\xi_1)\Big]_{-s}^{s},$$

where

$$A_2=a+\tfrac{1}{2}\frac{1}{f+a}\xi_2^2, \qquad A_1=a+\tfrac{1}{2}\frac{1}{f+a}\xi_1^2,$$

$$B_2=-\frac{1}{f+a}\xi_2, \qquad B_1=-\frac{1}{f+a}\xi_1,$$

$$C_2=-\frac{a}{2f(f+a)}\Big[1+\frac{f}{2a^2(f+a)}\xi_2^2\Big], \qquad C_1=-\frac{a}{2f(f+a)}\Big[1+\frac{f}{2a^2(f+a)}\xi_1^2\Big],$$

$$a_2=\frac{f+a}{\xi_2-\phi(f+a)}, \qquad a_1=\frac{f+a}{\xi_1-\phi(f+a)},$$

$$b_2=\frac{f+a,}{\{\xi_2-\phi(f+a)\}^2}, \qquad b_1=\frac{f+a}{\{\xi_1-\phi(f+a)\}^2},$$

$$c_2=\frac{f+a}{\{\xi_2-\phi(f+a)\}^3}+\frac{\xi_2(f+a)}{2a(f+a)\{\xi_2-\phi(f+a)\}^2},$$

$$c_1=\frac{f+a}{\{\xi_1-\phi(f+a)\}^3}+\frac{\xi_1(f+a)}{2a(f+a)\{\xi_1-\phi(f+a)\}^2}.$$

This expression has been used to determine the ratio of the intensities of the two edges for different positions of the advancing edge at different distances from the focal plane. The ratio of the brightness of the two edges was also determined experimentally by photometric comparison. For this purpose a double-image prism was used to obtain a pair of images of the luminous edges polarized in perpendicular planes which were then observed through a nicol. The results are shown in Table II. The agreement between theory and experiment is fairly satisfactory.

TABLE II

$2s = 3.47$ mm, $f = 43.3$ cm, $\lambda = 0.0006$ mm

a	ξ_1	ξ_2	Observed Ratio of the Intensity of the Two Edges	Calculated Ratio of the Intensity of the Two Edges
cm	mm	mm		
−4.0	0.85	5.65	0.25	0.21
−4.0	2.65	5.65	0.41	0.38
−2.5	0.72	5.38	0.32	0.30
−2.5	2.43	5.38	0.53	0.48
−1.5	1.00	5.95	0.50	0.45
−1.5	2.87	5.82	0.65	0.59
0	.....	.....	1.00	1.00
+2.5	0.76	5.76	1.32	1.28
+2.5	2.76	5.76	1.14	1.11
+4.5	0.61	5.61	2.37	2.29
+4.5	2.60	5.61	1.42	1.37

CALCUTTA UNIVERSITY
March 5, 1918

Minor Contributions and Notes

ON CHANGES OF THE WAVE-LENGTHS OF LINES IN STELLAR SPECTRA WITH CHANGE OF TYPE

In the March number of the *Astrophysical Journal*, Voûte has revived the research which was initiated in 1906, and continued in 1911, by Albrecht on the progressive changes of wave-length of stellar lines, depending on the stellar type. In some respects the results obtained by Albrecht were surprising. In the case of blended lines, especially if only two components were involved—and these perhaps of different types of line, such as enhanced and unenhanced—one would naturally expect a progressive change of position, depending on the alteration in relative intensity of the components as one proceeded along the various types; and, knowing the composition of the blends, it was fairly easy to predict which direction the changes in wave-length would take. Some of Albrecht's lines, however, were free from any suspicion of blending, and as these also showed progressive changes, obviously some other cause must be involved other than that recognized for the blended lines. Examples of this class of "pure" lines are Sc 4246.99, Cr 4254.51, Fe 4260.64, and p Ti 4468.66.

In other cases more than two lines compose the blends, and here the chances seem all against the changes taking place in one direction only, the cause being assumed to be the shift of the center of gravity of the blend, owing to relative changes in intensity among the various component lines. And yet Albrecht's results showed the same progressive changes for these as for the others. As examples of this class we may mention 4288.1, involving the solar lines Ti 4288.038, Ni 4288.149, and Ti-Fe 4288.310; 4315.1, composed of Ti 4314.964, p Ti 4315.138, and Fe 4315.262; and 4352.0, formed apparently by the two solar lines 4351.930 (due partly to p Fe line 4351.93 and partly to a Cr line of identical wave-length) and Mg 4352.083. For the last of these blends one would have

expected the lower wave-lengths to have prevailed toward the F end of the spectral types, as the enhanced lines are more prominent there, whereas the unenhanced lines of Cr and Mg are more pronounced in the solar and later types. Albrecht's values show an exactly contrary result, the wave-length diminishing in going from F to M. Although the line 4351.93, one of the components of this blend, is ascribed by Rowland to Cr only, there can be no doubt that in the solar line the enhanced line of Fe at 4351.93 is involved. In fact, if one goes farther back to the A and late B types, the evidence is almost overwhelming that in the former the stellar line in this position is due chiefly to p Fe, and in the latter wholly so.

Assuming Albrecht's results for the progressive changes in wave-length to be correct, no satisfactory explanation has been adduced in the case of unblended lines and complex blends involving more than two lines.

Voûte affirms that his resulting changes in wave-length agree on the whole with Albrecht's. There are, however, some very striking differences among the pure or unblended lines. Thus, for Sc 4247.0 Albrecht gets increased wave-lengths from F to K; Voûte's show a progressional decrease. For Fe 4260.6 Albrecht gets a continuous increase from F to K; Voûte's show an increase A to F, a big drop (0.16 A) F to G, then a bigger rise (0.24 A) G to K. For Cr 4274.96 Albrecht's decrease, Voûte's first decrease, then rise. For Hγ Albrecht's are nearly constant; Voûte's vary 0.1 A. In fact, of eight cases of unblended lines where the results of the two observers are comparable, only three show similar behavior. These are p Ti 4399.94, Fe 4469.55, and p Ti 4468.66.

In Voûte's own results for unblended lines there are one or two apparent inconsistencies in the wave-length changes for Fe lines which are always associated in laboratory spectra as being of similar behavior. Thus, for the two strong neighboring iron lines 4271.33, 4271.93, the former decreases from type A to F, then rapidly increases through type G to K, the variation being 0.18 A. The latter increases from A to F, falls from F to G, then rises rapidly to K, the whole range being 0.11 A. For the well-known Fe triplet 4383.72, 4404.93, 4415.29, whereas the two former have

nearly constant wave-lengths in the various stellar types, the last shows an increase continuously from A to K, and has a range of 0.13 A. It seems very probable that some of these results do not represent real changes, but are, in the main, due to errors in estimating the wave-lengths.

This kind of research is so important that it is to be hoped other observers with available material of the necessary refinement will undertake it, and thus afford comparison with Albrecht's consistent, though in some ways remarkable, results. Albrecht, in his paper of 1911, stated that he intended to continue the research, extending both the region of spectrum investigated and the range of stellar types, but, as far as the writer knows, he has not published anything further.

F. E. BAXANDALL

CAMBRIDGE, ENGLAND
May 23, 1918

SUGGESTION TO OBSERVERS OF NOVA AQUILAE

I desire to call the attention of observers who have powerful reflectors at their disposal to the desirability of making spectroscopic and polariscopic observations of the nebula which, judging from Nova Persei, may be expected to make its appearance about the new star in Aquila.

Attempts were made by the writer[1] to obtain such observations of the nebulosity about Nova Persei, but owing to the faintness of the nebulosity during the later stages when the attempts were made the results were not so decisive as could be desired, especially with regard to polarization.

It seems entirely possible with our present means to obtain decisive information on both of these points, if observations are made as soon as such nebulosity is well visible and separated from the star. In the case of Nova Persei, impressions of two nebulous rings were obtained about five weeks after maximum brightness. If Nova Aquilae behaves similarly, such nebulosity should be far enough away for separate observation in from two to three months

[1] *Lick Observatory Bulletins*, **1**, 180, 1902; **2**, 32, 1903.

from the date of the outburst, or in the month of August or September of the present year.

Such observations should throw light on the very important question whether the nebulosity is a product of the outburst or whether it existed in the region and may have been a factor in causing the outburst.

C. D. PERRINE

OBSERVATORIO NACIONAL ARGENTINO, CÓRDOBA
June 17, 1918

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